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EVALUATION SELECTION OF ENCAPSULATING PLASTICS FOR ORDNANCE ELECTRONIC ASSEMBLIES: FINAL REPORT

by S.J. Price, R.E. Isliefson, R.J. Ryan

Prepared by

HONEYWELL INC.
Defense Systems Division
Hopkins, MN 55343

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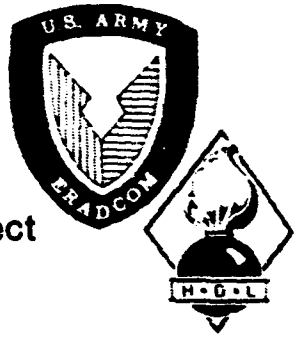

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A program was conducted to evaluate new plastics for encapsulating ordnance electronic circuits. Various candidate plastics including foams, syntactic resins, filled systems, semirigids, elastomers and molded thermoplastics and thermosets were evaluated through extensive mechanical and environmental tests followed by encapsulation of test circuits. Additionally, a relative cost comparison of the various material categories was conducted to identify and quantify cost drivers.

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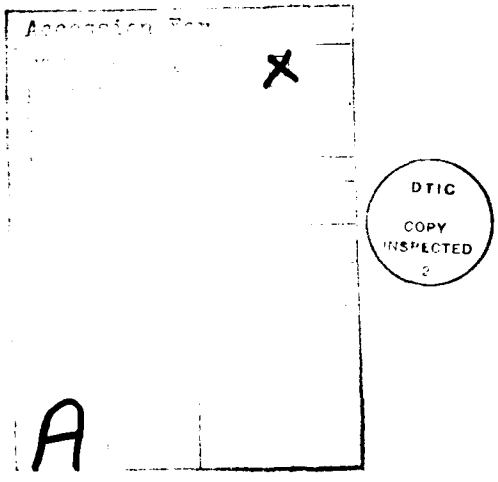
PREFACE

This report was prepared by Honeywell Inc., Defense Systems Division, 600 2nd Street NE, Hopkins, Minnesota 55343, under contract DAAK21-79-C-0017. This program was conducted for the Department of the Army, Harry Diamond Laboratories, Adelphi, Maryland, 20783. Mr. Allan Goldberg (DELHD-RT-CE) monitored the program for Harry Diamond Laboratories. Mr. Stephen J. Price, project engineer, directed the program at Honeywell. This program was conducted during the period from 8 January 1979 to 30 April 1980.



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CONTENTS

		Page
1.	INTRODUCTION	15
2.	STUDY PHASE	17
2.1	Liquid Systems	17
2.1.1	Introduction	17
2.1.2	Specification Development	18
2.1.2.1	Processing Parameters	18
2.1.2.2	Mechanical Properties	18
2.1.2.3	Thermal Properties	18
2.1.2.4	Electrical Properties	19
2.1.2.5	Chemical and Environmental Properties	19
2.1.3	Solicitation	19
2.1.4	Preliminary Screening	19
2.2	Nonliquid Moldable Systems	20
2.2.1	Introduction	20
2.2.2	Process Analysis	21
2.2.2.1	Injection Molding	21
2.2.2.2	Transfer Molding	22
2.2.3	Material Analysis	22
2.2.4	Information Gaps	22
2.3	Material Selection to 20 Candidates	25
3.	MATERIAL TESTING	28
3.1	Introduction	28
3.2	Chemically Blown Foams	28
3.2.1	Handling Evaluation and Identification	28
3.2.2	Demold Time Determination	29
3.2.3	Foam Flow Test	30
3.2.4	Glass Transition Temperature	31

CONTENTS (CONT'D)

		Page
3.2.5	Density and Compressive Strength	33
3.2.6	Hydrolytic Stability	33
3.2.7	Summary	34
3.3	Syntactic Foams	34
3.3.1	Handling Evaluation and Identification	36
3.3.2	Flexural Properties	37
3.3.3	Thermal Expansion and Glass Transition Temperature	37
3.3.4	Peak Exotherm and Embedment Stress	38
3.3.5	Thermal Shock	40
3.3.6	Tensile Shear Adhesion	43
3.3.7	Hydrolytic Stability	43
3.3.8	Summary	45
3.4	Rigid Filled Epoxy Compounds	45
3.4.1	Handling Evaluation and Identification	45
3.4.2	Flexural Properties	47
3.4.3	Thermal Expansion and Glass Transition Temperature	47
3.4.4	Peak Exotherm and Embedment Stress	48
3.4.5	Thermal Shock	49
3.4.6	Tensile Shear Adhesion	49
3.4.7	Hydrolytic Stability	49
3.4.8	Summary	49
3.5	Semirigid Urethanes (70D)	52
3.5.1	Handling Evaluation and Identification	52
3.5.2	Flexural Properties	52
3.5.3	Thermal Expansion and Glass Transition Temperature	53
3.5.4	Peak Exotherm and Embedment Stress	54
3.5.5	Thermal Shock	54
3.5.6	Tensile Shear Adhesion	55
3.5.7	Hydrolytic Stability	55
3.5.8	Summary	55

CONTENTS (CONT'D)

			Page
3.6	Elastomers (<70D)		55
	3.6.1	Handling Evaluation and Identification	57
	3.6.2	Tensile Properties	58
	3.6.3	Glass Transition Temperature (T_g)	58
	3.6.4	Peel Strength	59
	3.6.5	Thermal Stability	59
	3.6.6	Hydrolytic Stability	59
	3.6.7	Summary	61
3.7	Injection Molded Compounds		61
	3.7.1	Demold Times	62
	3.7.2	Glass Transition Temperature (T_g)	62
	3.7.3	Compressive Properties	62
	3.7.4	Hydrolytic Stability	62
	3.7.5	Summary	64
3.8	Transfer Molded Thermoset Compounds		64
	3.8.1	Demold and Cure Evaluation	65
	3.8.2	Flexural Properties	65
	3.8.3	Thermal Expansion (CTE) and Glass Transition Temperature (T_g)	65
	3.8.4	Hydrolytic Stability	65
	3.8.5	Summary	66
3.9	Material Selection to 10 Candidates		66
4.	CIRCUIT ENCAPSULATION		69
4.1	Introduction		69
4.2	Circuit Types		69
	4.2.1	Thick-Film Hybrid Circuit	69
	4.2.2	Glass-Epoxy (G-10) Printed Circuit Board	71
4.3	Encapsulation Technique		71
	4.3.1	Liquid Encapsulants	71

CONTENTS (CONT'D)

			Page
	4.3.2	Transfer Molding Technique	71
4.4		Circuit Testing	74
4.5		Results	74
	4.5.1	Cook Coro-foam 589 Urethane Foam	74
	4.5.2	Witco Isofoam PE-18 Urethane Foam	74
	4.5.3	Formulated Resins PR 2036 Two-Component Syntactic Foam	77
	4.5.4	3M Scotchcast XR5090 Two-Component Syntactic Foam	77
	4.5.5	Hysol NB509-70-2 Single-Component Syntactic Foam	77
	4.5.6	Emerson and Cuming Stycast 1495/Catalyst 9 Filled Epoxy	77
	4.5.7	Hysol E-0029 Single-Component Filled Epoxy	77
	4.5.8	Hysol Hiflow MG5F Transfer Molding Epoxy	78
	4.5.9	Dow ISP-100 Semirigid Urethane	78
	4.5.10	Uniroyal B635/1,4-BD Flexible Urethane	78
4.6		Selection of Five Materials	78
5.		COST ANALYSIS	80
5.1		Introduction	80
5.2		Assumptions	80
	5.2.1	Production Volume	80
	5.2.2	Production Facility	81
	5.2.3	Labor Rates	81
	5.2.4	Material Volume	81
	5.2.5	Material Categories	81
5.3		Material Comparisons	83
5.4		Mold Concept Comparisons	83
5.5		Conformal Coating	87
5.6		Effect of Cure Time	88
5.7		Effect of Number of Components	89

CONTENTS (CONT'D)

Page

5.8 Effect of Cure Temperature 90
5.9 Liquid versus Transfer Molding 91
5.10 Cost Drivers 92

6. SUMMARY AND CONCLUSIONS 93

APPENDIX A MOLD COST COMPARISONS: TOOLING FOR MOLDS 95

APPENDIX B STRESS RELIEF COATING: SUMMARY 99

APPENDIX C MATERIAL TYPE COST COMPARISON 103

APPENDIX D INFRARED SPECTRA FOR 10 CANDIDATE MATERIALS 117

DISTRIBUTION LIST 127

FIGURES

Figure		Page
1	Foam flow test	32
2	Hydrolytic stability results	35
3	Embedment stress test setup	39
4	Embedment stress test results (150-ml beaker)	41
5	Embedment stress test results (100-ml beaker)	42
6	Hydrolytic stability test results (syntactic foams)	44
7	Hydrolytic stability test results (filled epoxy)	51
8	Hydrolytic stability test results (semirigid urethanes [>70 D])	56
9	Hydrolytic stability test results (castable elastomers [<70 D])	60
10	Thermoplastic foam (Uniroyal E-80) hydrolytic stability	63
11	Thermoset material hydrolytic stability	67
12	M734 amplifier thick-film hybrid circuit	70
13	Discrete component circuit	72
14	Mold for a circuit encapsulation with liquids	73
15	Comparison of recurring and nonrecurring costs	84
16	Breakdown of recurring costs	85

TABLES

Table		Page
I	THERMOPLASTIC MATERIAL ANALYSIS	23
II	THERMOSET MATERIAL ANALYSIS	24
III	TWENTY CANDIDATE MATERIALS	26
IV	HANDLING EVALUATION OF CHEMICALLY BLOWN FOAMS	29
V	DEMOLD TIME OF CHEMICALLY BLOWN FOAMS	30
VI	GLASS TRANSITION TEMPERATURE OF CHEMICALLY BLOWN FOAMS	31
VII	DENSITY AND COMPRESSIVE STRENGTH OF CHEMICALLY BLOWN FOAMS	33
VIII	HYDROLYTIC STABILITY OF CHEMICALLY BLOWN FOAMS	34
IX	HANDLING EVALUATION OF SYNTACTIC FOAMS	36
X	FLEXURAL PROPERTIES OF SYNTACTIC FOAMS	37
XI	THERMAL EXPANSION AND GLASS TRANSITION TEMPERATURE OF SYNTACTIC FOAMS	38
XII	PEAK EXOTHERM OF SYNTACTIC FOAMS	40
XIII	HYDROLYTIC STABILITY OF SYNTACTIC FOAMS	43
XIV	HANDLING EVALUATION OF FILLED EPOXY	46
XV	FLEXURAL PROPERTIES OF FILLED EPOXY	47
XVI	COEFFICIENT OF THERMAL EXPANSION AND GLASS TRANSITION TEMPERATURE OF FILLED EPOXY	48
XVII	PEAK EXOTHERM TEMPERATURE OF FILLED EPOXY	48
XVIII	HYDROLYTIC STABILITY OF FILLED EPOXY	50
XIX	HANDLING EVALUATION OF SEMIRIGID URETHANES	52
XX	FLEXURAL PROPERTIES OF SEMIRIGID URETHANES	53

TABLES (CONT'D)

Table		Page
XXI	THERMAL EXPANSION AND GLASS TRANSITION TEMPERATURE OF SEMIRIGID URETHANES	54
XXII	PEAK EXOTHERM OF SEMIRIGID URETHANES	54
XXIII	HYDROLYTIC STABILITY OF SEMIRIGID URETHANES	55
XXIV	HANDLING EVALUATION OF ELASTOMERS	57
XXV	TENSILE PROPERTIES OF ELASTOMERS	58
XXVI	THERMAL STABILITY OF ELASTOMERS	59
XXVII	HYDROLYTIC STABILITY OF ELASTOMERS	6
XXVIII	COMPRESSIVE PROPERTIES OF THERMOPLASTIC FOAM (UNIROYAL E80)	6
XXIX	HYDROLYTIC STABILITY OF THERMOPLASTIC FOAM (UNIROYAL E80)	64
XXX	FLEXURAL PROPERTIES OF MOLDED THERMOSET MATERIAL (HYSOL MG5F)	65
XXXI	THERMAL PROPERTIES OF MOLDED THERMOSET MATERIAL (HYSOL MG5F)	65
XXXII	HYDROLYTIC STABILITY OF MOLDED THERMOSET MATERIALS	66
XXXIII	TEN CANDIDATE MATERIALS	68
XXXIV	ENCAPSULATION RESULTS	75
XXXV	MATERIAL COSTS	82
XXXVI	EFFECT OF TOOLING CONCEPTS (1-HOUR DEMOLD)	86
XXXVII	EFFECT OF CONFORMAL COATING WITH TWO-COMPONENT RIGID, FILLED EPOXY	87

TABLES (CONT'D)

Table		Page
XXXVIII	EFFECT OF CURE TIME (RIGID EPOXY)	88
XXXIX	EFFECT OF NUMBER OF COMPONENTS (RIGID EPOXY).....	89
XL	EFFECT OF PROCESSING TEMPERATURE (CHEMICALLY BLOWN FOAMS)	90
XLI	LIQUID VERSUS TRANSFER MOLDED	91
XLII	MAJOR COST DRIVERS	92

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1. INTRODUCTION

Ordnance electronic circuitry and components are commonly encapsulated within a plastic material molded so as to provide mechanical, electrical, and environmental protection during their assembly, storage, and function. The degree of protection required is dependent on the type of circuitry and the functional requirements of the device. These requirements can vary from hand emplacement, in which little mechanical support is required, to artillery or mortar deployment, which involves high setback forces.

Depending on the application, the encapsulant chosen might therefore be an elastomer, a rigid foam, or a rigid highly filled epoxy material. Most encapsulants currently in use can require many hours of cure time in fixtures or molds. This results in high production costs due to the capitalization of equipment, tooling, energy consumption, and space.

The objective of this program is to evaluate commercially available materials and processes which meet different ordnance requirements but all of which have rapid processing times and, hence, reduced production costs. The selection of materials represented innovative approaches to encapsulation, such as liquid transfer molding (LTM), the reaction injection molding (RIM) of liquids, and the transfer or injection molding of solids as well as the more conventional approaches to encapsulation such as foam-in-place or the casting of epoxy or urethane materials.

In addition to identifying materials which meet these goals, the cost of these various systems was identified for a typical configuration in high-volume production (100,000 units per month). From this, the cost was analyzed for each major segment of encapsulation and the cost drivers quantified.

The goals of each major phase of the program were defined as follows:

1. Study Phase -- The initial phase of this contract was to review the state of the art and appropriate specifications to identify the materials and processes most compatible with electronic circuit encapsulation. This included the generation of a specification for each major class of material, vendor contacts, and the preliminary screening on a large number of materials and approaches. This activity culminated in a design review in which 20 materials were selected for the next phase.

2. Material Testing Phase -- The second phase concentrated on the evaluation of candidate materials to meet specific test requirements required for electronic encapsulation. These tests consisted primarily of ASTM and military specification procedures established during the

program and included tests specific to each material type. This effort culminated in a second design review in which 10 materials were selected for further evaluations.

3. Electronic Circuit Encapsulation Phase -- The third phase developed the tooling and procedures for encapsulating hybrid and discrete electronic circuits. After an initial 100 circuits, a third design review was held to review these results and select five materials from which an additional 50 circuits were encapsulated. The encapsulated modules were delivered to HDL for further testing. The results of these tests will be reported separately by HDL.

4. Cost Analysis Task -- This final phase of the contract developed a comparison of the costs inherent in the various encapsulation processes. The recurring and nonrecurring costs were identified and quantified. Results were then analyzed to identify the cost drivers of various encapsulation systems. These cost drivers included the effect of material type, cure time, temperature, mold types, and molding approaches.

2. STUDY PHASE

2.1 Liquid Systems

2.1.1 Introduction

The electronics in ordnance circuitry encompasses a wide range of components and configurations. In discrete component packages, components such as transistors, transformers, capacitors, precision resistors, and glass diodes are particularly sensitive to the temperature and pressure of encapsulation. Other components such as resistors, prepotted torroidal coils, dual-in-line packages, and components prepackaged in hermetically sealed packages are less sensitive to the environments presented during and after encapsulation.

While discrete circuits are complex in componentry, they traditionally are prepared as a glass/epoxy circuit board in which the coefficient of thermal expansion is reasonably matched to most encapsulants. In hybrid circuitry, this substrate is more likely to be ceramic and, thus, much less tolerant to the differential forces exerted by the plastics used to encapsulate the circuit. The componentry on hybrid circuits is ruggedized by virtue of size and low profile on the substrate. However, a failure in the ceramic substrate usually results in a totally failed circuit.

The presence, location, and orientation of these components will often define the process limitations including mold design, material entry direction and rate, and the uncured material characteristics required.

Circuit complexity also influences the viscosity and gel time requirements for a material so as to ensure the complete fill of the module during encapsulation. During the cure cycle, the exotherm and shrinkage of the compound must be controlled to avoid excessive temperatures and pressures. Once cured, the encapsulant must provide the mechanical, electrical, and environmental protection required. At the same time, the encapsulant must not exert excessive stress on components due to embedment stress or mismatches in coefficients of thermal expansion during thermal cycling.

There are three major categories of liquid plastic technologies which are conventionally used in electronic encapsulation: rigid foams; filled rigids; and semiflexible or flexible compounds. Each of these has one or more subgroups, such as syntactic (glass bubble filled), rise-in-place foams, and single or multiple components.

2.1.2 Specification Development

To identify and select the materials which could successfully perform in accordance with these diverse and often conflicting requirements, a specification was prepared to which vendors of liquid polymers were requested to supply data and samples.

In this specification, the key parameters of liquid encapsulants were defined and limits established such that vendors could prescreen their current materials which may be of interest.

2.1.2.1 Processing Parameters

- Processing temperature of less than 200°F (preferably between room temperature and 160°F).
- Demold time of one hour at the most, or the ability to be catalyzed in less than one hour.
- Pressure generated during encapsulation to be less than 500 psi.
- One or two-component systems.
- Mix ratio and viscosities compatible with meter-mix/dispensers.

2.1.2.2 Mechanical Properties

- Hardness
  - elastomers (less than 70 Shore D)
  - semirigids (greater than 70 Shore D)
  - filled rigid (60-90 Shore D)
- Density
  - Chemically blown foams (6 to 30 lb/ft^3)
  - syntactic foams (30 to 60 lb/ft^3)
  - filled rigid (90 to 150 lb/ft^3)
- High flexural and compressive strength
- Minimum modulus change from -65°F to +160°F
- Capable of withstanding mechanical shock of 3,000 to 30,000 g depending on material type.

2.1.2.3 Thermal Properties

- Pass hex bar thermal shock per MIL-I-16923.

- o Low coefficient of thermal expansion.
- o Glass transition temperature not between -65°F and 160°F.

2.1.2.4 Electrical Properties

- o Volume resistivity above 10^{12} ohm-cm.
- o Dielectric constant of less than 5.0 when measured between 60 and 10^6 Hz.
- o Dissipation factor of 0.05 maximum when tested between 60 and 10^6 Hz.

2.1.2.5 Chemical and Environmental Properties

- o Noncorrosive to copper, aluminum or steel.
- o Nontoxic or nonhazardous when properly handled.
- o Capable of passing 120-day hydrolytic stability test per MIL-I-16923.
- o Water absorption of less than 0.2 percent in 24 hours.

2.1.3 Solicitation

A comprehensive vendor list of material manufacturers and formulators was established. Distributors of materials were not included. The key technical people in each organization were contacted by phone, the program explained, and initial interest and products determined. Following this initial contact, a letter containing the material specification was sent. A phone follow-up was conducted to answer any questions and to ensure a timely response.

More than 90 material suppliers were contacted by this process. Approximately 50 suppliers responded, with 75 products identified. The data sheets of these products were reviewed as to their applicability, and the properties reported were examined. None of the product data sheets contained all of the test data required to select materials for ordnance encapsulation. A compilation of this data was prepared and 35 samples requested for preliminary screening.

2.1.4 Preliminary Screening

As samples were received, some key parameters were checked. These varied in different samples, but usually involved the observations of viscosity of the components, the extreme settling of fillers, odor, and, in some instances, the cure rates. These preliminary observations were performed to spot-check and verify expectations rather than to obtain firm data.

This data, along with other products totaling 71 materials, was presented and discussed with HDL during the first design review.

The data indicated that the following number of candidates were in the seven categories:

1.	Chemically Blown Foams -	11 Materials
2.	Two-Component Syntactic Foams -	8 Materials
3.	One-Component Syntactic Foams -	3 Materials
4.	Two-Component Filled Epoxy -	25 Materials
5.	One-Component Filled Epoxy -	6 Materials
6.	Two-Component Semirigid (70D) -	7 Materials
7.	Elastomers (70D) - .	11 Materials
	Total	71 Materials

(A further discussion of this review and of the selection of products for further testing can be found in Section 2.3.)

2.2 Nonliquid Moldable Systems

2.2.1 Introduction

Electronic circuitry is usually encapsulated with liquid plastics. Many components, such as dual-in-lines, are successfully prepackaged with thermoplastic or thermoset molding compounds.

Thermoplastic and thermoset molding compounds are inherently fast-cycle-time materials for which well-developed equipment and processes are used to produce high volumes of plastic parts. For example, times as low as 15 to 30 sec can be achieved. Molding compounds require significantly higher processing temperatures and pressures. The viscosity and flow rates during encapsulation therefore create much higher wave fronts moving across the circuit, for which mold design and circuit protection techniques must be developed. As a result, the adaptability of these processes for encapsulating electronic circuitry requires a good deal of rethinking in circuit design, component selection, material requirements, and control of the molding process in order to result in successful application of this approach.

Considerable work has been done studying the effects of molding on discrete circuits (Westinghouse, Contract DAAH01-68-C-2020 [1,2]) for the U.S. Army Missile Command at Redstone Arsenal, Alabama. This study concerned transfer molding techniques for encapsulating electronic modules. After this extensive test program involving design criteria, process effects, and process parameters, it was concluded that discrete components do exist in each category which will withstand this process.

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1. Harper, C.A. et al, "Guidelines for Transfer Molding Electronic Modules," Westinghouse Electric Corp. Baltimore, MD, AD-871-917. March, 1970

2. Ibid; Data Volume AD-871-826. March, 1970

The adapability of these systems for discrete or hybrid electronic circuitry was studied for feasibility. The materials were researched for data and cavity behavior during molding, effects on circuitry, and concepts to protect the circuitry. While this activity quickly grew beyond the scope of this contract, several major information gaps were defined for further study.

2.2.2 Process Analysis

2.2.2.1 Injection Molding

Injection molding is a very rapid processing technique used for thermoplastics, as well as for some thermoset and elastomer formulations. With thermoplastics, typical total cycle times of 30 sec to 3 min can readily be achieved without further processing. The electronic module would be used as an insert in the molding process.

In this process, the resin is plasticized and melted in a heated screw cyclinder and injected into a closed cavity with high pressure. Temperature of the melt ranges from 350°F to more than 600°F depending on the type of material. Pressures of up to 20,000 psi are used to "pack" the mold.

While these processing parameters appear to be far higher than the limits allowable for electronics, several concepts offer some potential. By choosing lower temperature processable polymers, short cycles, and cool molds, a minimum temperature exposure to the module can be achieved.

Additional cooling may be achieved with heat-pipe cooling standoffs or precooled circuit boards. The boards may also achieve some thermal protection with the use of conformal coatings.

The pressures exerted on the components by the rapid material flow into the cavity may be reduced by gating to direct the melt front toward the cavity wall and from the wall onto the module. The choice of material can also result in low viscosity melts, requiring lower injection pressures. When a foaming agent is used with thermoplastics, a partial fill of material is introduced into the mold and allowed to "foam" (expand) to fill the cavity at very low cavity pressures (less than 500 psi).

A review of recent literature found little information on the rheology of thermoplastics during molding and its effects on delicate inserts.

2.2.2.2 Transfer Molding

In transfer molding, the circuit module would again be used as an insert in the mold. The material in the form of a preform or powder is forced into the cavity with a transfer ram or pot. During this transfer operation, the material goes into a melt phase and fills the cavity. The pressures exerted are far less than injection molding and can be as low as 50 to 100 psi. The materials used do require chemical cures in the mold. However, cycles of one to five minutes at 250 to 300°F are possible. Some low-temperature postcuring may be required on some systems. Techniques for cooling during the molding cycle are similar to those described under injection molding.

2.2.3 Material Analysis

A review of commercially available materials concentrated on the temperature and pressure parameters as well as on the exposure time and mechanical properties. Table I is a list of typical thermoplastic materials. This table shows several materials in which the process temperature of the plastic is below 350°F, with injection molding pressures of less than 8000 psi: polyethylene, EEA, ionomers, and cellulosics. The majority of engineering thermoplastics, such as nylon, polyesters, and polycarbonate, have molding temperatures in excess of 500°F with pressures reaching 15,000 psi. The mechanical properties of most of these materials exceed the liquid resin counterparts.

Table II shows a similar analysis for common thermoset compounds. From this table, most of the materials cure at less than 350°F with pressures as low as 400 psi. Recognize that there are several materials within each thermoset class, some of which are made specifically for the low-pressure encapsulation of electrical components. The mechanical strengths of these materials compare favorably with liquid rigid materials.

2.2.4 Information Gaps

In reviewing these concepts, several questions arose that were not answered by available information and for which data would have to be collected and concepts developed to successfully apply this molding technology to electronic circuit encapsulation. These include a better understanding of material properties during processing, circuitry tolerances and effectiveness of circuit protection techniques.

During the processing of thermoplastics and thermosets the high temperature and pressures during cavity filling create wave-front dynamics which interact with inserts in the mold. An understanding of how these viscous materials fill the cavity and the mold designs needed to control the material

TABLE I. THERMOPLASTIC MATERIAL ANALYSIS

Material	Initial Molding Temperature, °F	Initial Molding Pressure, psi (Minimum)	Mold Temperature, °F	Demold Time 1/4-in. Section	Coefficient of Thermal Expansion, x 10^{-5} in./in./°C	Flexural Modulus x 10^5 psi	Compressive Strength, psi
ABS	450-525	8,000	130	2 min	6.0-9.0	2.0-3.5	4,500-9,000
Acetal	400-450	10,000	180	2 1/2-2 min	8.1	4.1	18,000
Acrylic	340-425	10,000	150	1-1 1/2 min	5.0-9.0	1.5-1.7	12,000-18,000
Ionomer	300-500	5,000	--	--	12	.3	--
Nylon 12	302	4,000	140	70-80 sec	19.4	1.7-1.8	--
Nylon 6	450-550	3,000	140	70-80 sec	8.3	.8-1.4	6,700-13,000
Nylon 6/6	530-580	9,000	160	60-70 sec	8.0	1.75	6,700-12,500
Nylon 6/12	450-550	9,000	120	50-60 sec	9.0	1.6	--
Noryl	550-600	14,000	180	--	5.7-6.1	3.75-4.0	10,400-12,000
Polycarbonate	500-600	10,000	200	60-70 sec	6.6	3.4	12.5
Polyester	450-500	8,000	240	1 1/2-2 min	6.0	4.0	18,600
LDPE	350-450	6,000	80	80-90 sec	10.0-20.0	0.8-.6	--
MDPE	350-450	6,000	80	60-70 sec	14-16	.6-1.15	--
HDPE	400+	8,000	80	50-60 sec	11-13.0	1.0-2.5	2,700-3,600
Ethylene ethyl acrylate	250+	8,000	100	2 min	--	--	--
PP	400+	8,000	100	60-70 sec	5.9-10.2	2.0-2.4	5,500-8,000
Polybutylene	290+	10,000	--	--	15	.49	--
TBX	500	8,000	110	70-80 sec	11.7	--	--
Polysulfone	650+	15,000	160	60-70 sec	5.2-5.6	3.7-3.9	18,900
Cellulosic	335	8,000	--	--	8-18	1.1-2.4	3-10,000

TABLE II. THERMOSET MATERIAL ANALYSIS

Material	Mold Temperature, °F	Transfer Pressure, psi	Demold Time 1/4-in. Section	Spiral Flow, in. (ASTM D-3123)	Coefficient of Thermal Expansion x 10^{-5} in./in./°C	Flexural Modulus x 10^{6} psi	Compressive Strength, psi
Epoxy	250-300	50-1,000	4 min	100	1.1-5.0	1.7	31,200
DAP	270-350	1,000-8,000	4 1/2 min	14-20	1.0-6.0	--	20-35,000
Alkyd	250-330	400-800	50 sec	--	1.5-5.5	1.7-2.0	20-35,000
Melamine	270-330	1,500	5 min	--	1.5-4.5	1.1-2.0	25-35,000
Phenolic	250-350	2,000	3 min	--	0.8-4.5	1.0-3.0	10-30,000
Silicone	300	400	5 min	38	0.8-4.5	1.7	14,500

during molding is required to assess the environment in which the circuit must survive. The temperature and the time at temperature as well as the cooling rates and embedment stresses generated during cooling are other aspects.

The circuit required to survive this molding will require proper component selection and location to survive the temperature and pressures generated in this process. The effects of short-term, high-temperature thermal shock and embedment stresses are expected to be significantly different than those experienced in liquid encapsulation. Each circuit must be designed for this process as well as for electronic function. Improvements may be required in components and their mechanism of attachment to circuit boards to allow for these higher temperatures and pressures.

As a compromise, methods of protecting circuitry during molding would have to be developed in which the temperature and pressure inherent with these processes could be reduced. This may involve heat sinking, coatings, or the prepackaging of the circuitry to enhance survival.

Finally, molded electronic packages must be tested to verify that circuits are protected in ordnance environments without affecting performance.

All of these factors must be evaluated and optimized to achieve the capability of insert molding electronic modules in high volume production. The feasibility exists and the cost tradeoffs would be very favorable if these technologies were to be adopted for ordnance electronic encapsulation.

2.3 Material Selection to 20 Candidates

The first design review was held to select up to 20 candidates for further evaluation. The selection was made from both liquid and nonliquid systems. Commercially available products with moderate cure temperatures which showed the capability of demold times of less than one hour were selected. In addition, candidates were viewed as to innovativeness or improvement over commonly used encapsulants. The selection of these materials does not necessarily imply that these are the best materials in industry for encapsulation but rather are the result of the various tradeoffs described above and the time limitations of this program.

Table III lists the materials chosen from the study phase for further evaluation. The materials selected represent each of the major plastic categories. Three materials, Witco Isofoam PE18, Uniroyal B635, and Epic Resins R1016, were used as standards in that either HDL or Honeywell had previous field experience with these materials in ordnance devices.

TABLE III. TWENTY CANDIDATE MATERIALS

A. Chemically Blown Foams

1. Chemetics CSI-740-(18-20)
2. Cook Coro-foam 589
3. Formulated Resins PR2028
4. Witco Isofoam PE-18

B. Two-Component Syntactic Foams

1. Formulated Resins PR2036
2. 3M Scotchcast XR2090
3. Emerson and Cuming LTM-LM 79055

C. One-Component Syntactic Foams

1. Hysol NB 5090-70-2

D. Two-Component Filled Epoxy

1. Emerson and Cuming LTM-LN79054
2. Emerson and Cuming Stycast 1495/Catalyst 9
3. Epic Resins R1016/H5008

E. One-Component Filled Epoxy

1. Hysol EO-0029

F. Semirigid (70D)

1. Emerson and Cuming Stycast LN29805

TABLE III. TWENTY CANDIDATE MATERIALS (Cont'd)

2. Conap EN24
3. Dow Chemical ISP-100 (XD-8793.01, XD-8792.00, stannous octoate)
4. Arnco PSX-75D

G. Elastomers (70D)

1. Uniroyal B635/1,4 Butanediol
2. Castall CU 2008 R+I
3. Hysol NB2090A+B

H. Transfer Molded

1. Hysol Hiflow MG5F

I. Injection Molded

Uniroyal E-80 with 1.0 pph LNP FoamKon 23 blowing agent to produce a 30% void, structural foam

3. MATERIAL TESTING

3.1 Introduction

The selection of encapsulants for electronic circuitry requires laboratory testing in a variety of environments to predict the behavior of these materials in use. Appropriate ASTM and military specification tests were used to measure the bulk properties on the material classes selected in the study phase. Those tests selected represented mechanical, thermal, and long-term aging properties which approximate the environment that an encapsulant must experience in conjunction with electronic circuitry when used with ordnance. In addition, the processing and cure properties of the materials were evaluated to ensure compatibility in encapsulation.

Following these tests, the results were reviewed and 10 materials selected for the next phase which involved the encapsulation of electronic modules.

3.2 Chemically Blown Foams

Chemically blown foams are two-component liquid systems which, when mixed together, release a blowing agent. The foaming action is rapid, with rise times of one to ten minutes, depending on the speed of the system. Immediately after the foam has risen to fill the enclosure and expend the blowing agent, the material cures to a point of retaining the cell structure. This phenomenon is rapid and can be completed and the parts handled in 15 minutes to several hours.

Rigid foams provide considerable protection to potted electronic assemblies in the low to medium mechanical-shock range. Foams may also be useful at high shock levels, but the upper limit has not been as well defined for foams as it has for rigid epoxy systems. Rigid foams are highly adaptable to automatic dispensing. Their high reactivity and short cream and rise times make their use more feasible for liquid transfer molding than for automated casting techniques.

3.2.1 Handling Evaluation and Identification

The initial observation of the four foam candidates was the evaluation of their handling characteristics. This involved observing the viscosity of the components, the mix ratio, processing temperatures, the ease of mixing, cream time (the start of the blowing action), and the rise time of the foam.

Table IV summarizes these observations. The viscosity of all of the candidates was less than 5000 cps for Part A and less than 7500 cps in Part B. The mix ratio of the candidates was very compatible with automatic dispensing equipment at nearly a 1:1 ratio. A cream time of 30 seconds to a minute was

measured at room temperature, which is sufficient to allow a thorough mixing. Rise times of 2 to 4 minutes were measured, which are slow enough to allow the material to flow to the bottom of a complex cavity and rise at a rate which should not put excessive stress on components.

TABLE IV. HANDLING EVALUATION OF CHEMICALLY BLOWN FOAMS

Parameters	Chemetics CSI-740	Cook Coro-foam 589	Formulated Resins PR2028	Witco Isofoam PE-18
Viscosity (cps)				
Part A	200-300	200-250	250	4500
Part B	850-950	1800-2300	1600	6500
Mix ratio	1:1	1:1	100:115	100:75
Process temperature (^{o}C)	23	23	23	23
Cream time (sec)	50-60	30	50-60	20
Rise time (sec)	195-210	280	120-180	360
Isocyanate type	MDI	MDI	MDI	TDI
Blowing agent	CO_2	CO_2	CO_2	CO_2

An infrared scan was made on each component of the materials. The Chemetics, Cook, and Formulated Resin foams are carbon-dioxide blown MDI urethane foams, while the Witco foam is a carbon-dioxide blown TDI urethane. The toxicity of MDI foams is far less than that of TDI-based systems.

Since the observations on handling showed only minor differences, the processing capability of the three materials was judged to be equivalent or superior to the Witco PE-18 being used as a standard.

3.2.2 Demold Time Determination

To achieve a rapid processing objective, the time required for the foam to reach a condition of cure in which it can be removed from a fixture without damage or future dimensional change was measured. A quantity of material was free-formed into 2.5-inch diameter cylinders to achieve a 1 to 1.5-inch height. The time to demold was measured as a successful removal from the cylinder

without damage. Samples were prepared and observed at 15-minute intervals. When the foam sample was removed without deformation, the dimensional stability was measured by allowing the sample to cure 7 days at room temperature, followed by a 24-hour exposure at 71°C. The diameter of the sample was recorded immediately after demolding, and again after the sample reached ambient conditions. The demold time was derived by selecting the shortest cure time at room temperature which would achieve dimensional stability.

Table V summarizes the data measured. The three MDI systems had demold times of less than two hours. The Cook Coro-foam 589 was demoldable in 15 minutes with excellent dimensional stability. The TDI system, Witco Isofoam PE-18, exhibited a long period of friable behavior in which the sample was brittle and crumbly. A 16-hour cure time in the mold was required to achieve a damage-free sample.

TABLE V. DEMOLD TIME OF CHEMICALLY BLOWN FOAMS

Parameter	Chemetics CSI-740	Cook Coro-foam 589	Formulated Resins PR 2028	Witco Isofoam PE-18
Time at 23°C required to demold, hours:	2.0	0.25	1.5	16.0
Dimensional stability of a molded cylinder 2.5-inch dia. X 1.0-inch height aged 24 hours at 71°C				
Percent dia. change:	+1.3	+0.2	-0.6	+1.3

3.2.3 Foam Flow Test

The ability of a foam to fill in restricted areas during the rise time is critical in electronic encapsulation because complete fill around complex components is required to achieve uniform mechanical support. This fill ability was measured by a flow test initially developed by Honeywell[3] in which a quantity of foam is required to rise through a roll of single-sided corrugated paper. The height and uniformity of fill are then measured by sectioning the corrugation lengthwise and crossways.

3. Johnson, L.I., and Ryan, R.J., Honeywell Inc., "Flow Test for Foams," presented at the Electrical Insulation Conference, 1973 (Chicago)

A one-quart metal can was used with a continuous, tightly-rolled, Type A single-sided paper corrugate. The roll diameter was 4.125 in. and corresponded to the container diameter. A calculated amount of mixed foam equalling 187 cm^3 was introduced into the can and the corrugate positioned 2 in. above the bottom of the can to allow the foam to rise. After a 7-day-at-room-temperature cure, the foamed samples were sectioned in two directions. The height was measured and the percentage of fill calculated to the point at which all sections of the corrugate were completely filled.

Figure 1 shows one section cut of the four foams evaluated. Of the materials tested, the Witco PE-18 showed a significantly higher fill percentage than the MDI systems. All four of these systems, however, filled significantly better than did the foams for which the test was developed.

This test confirms that these foams have sufficient rise times and low viscosities during rise to allow complete filling in complex moldings.

3.2.4 Glass Transition Temperature

A material must protect electronics from high temperatures in ordnance devices. The material should maintain a nearly uniform profile throughout the functional temperature range of -40°C to +71°C. To ensure this, each candidate was measured for its glass-transition temperature using thermal-analysis techniques.

The glass transition temperature (T_g) is the temperature at which a polymeric material changes characteristics from one set of properties to another (i.e., from a tough to a brittle glass-like material). This change is accompanied by a shift in the coefficient of thermal expansion (CTE), which is an easy measure of this phenomena. A Perkin-Elmer Thermomechanical Analyzer (TMA), Model TMS-1, was used to scan the thermal expansion from +23°C to +100°C at the rate of 10°C/minute. The point at which the slope of the thermal expansion changed was interpreted as the glass transition temperature.

Table VI shows that only the Cook Coro-foam 589 has a glass transition temperature above 71°C.

TABLE VI. GLASS TRANSITION TEMPERATURE OF CHEMICALLY BLOWN FOAMS

Foam	Glass Transition Temperature (T_g)
Chemetics CSI-740	+64°C
Cook Coro-foam 589	+81°C
Formulated Resins PR 2028	+60°C
Witco Isofoam PE-18	+55°C

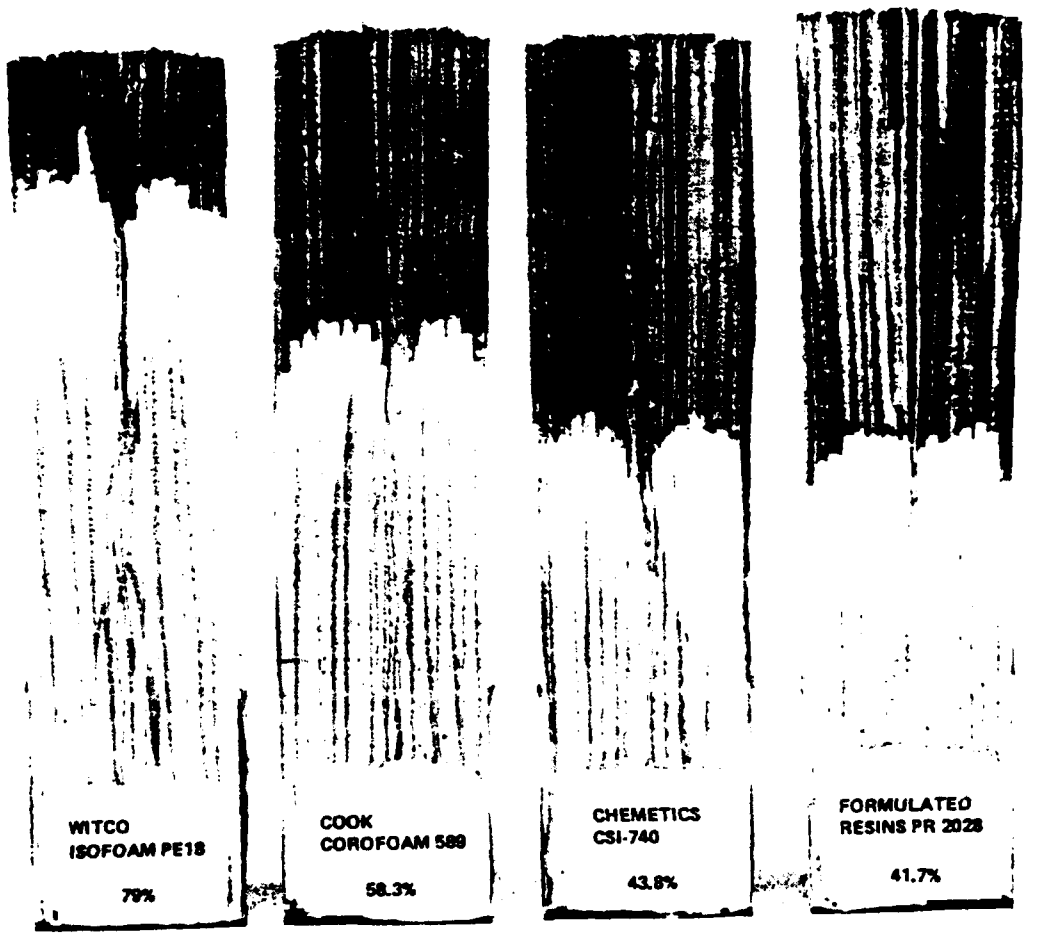

Figure 1. Foam flow test.

3.2.5 Density and Compressive Strength

A free-foamed sample of each foam was prepared in a six-inch diameter cylinder. One-inch-square blocks were sawed and the average core density measured per ASTM-D-1622. Additional samples were used to measure the compressive strength and compressive modulus at -40°C, 23°C, and 71°C per ASTM-D-1621. The samples were measured in the direction of foam rise.

The data measured (Table VII) shows that the compressive strengths are within those expected at the densities achieved[4]. Of the 15 to 16 lb/ft^3 foams, the Cook Coro-foam 589 comes closest to the properties of the Witco Isofoam PE-18 standard.

TABLE VII. DENSITY AND COMPRESSIVE STRENGTH OF CHEMICALLY BLOWN FOAMS

Parameter	Chemetics CSI-740	Cook Coro-foam 589	Formulated Resins PR2028	Witco Isofoam PE-18
Density, lb/ft^3	15.2	16.2	9.1	15.5
Compressive strength, psi, at				
-40°C	930	1,120	148	1,100
23°C	645	750	130	790
71°C	440	505	104	590
Compressive modulus, psi, at				
-40°C	23,800	31,700	4,840	26,700
23°C	19,100	25,000	3,150	25,500
71°C	10,600	15,200	2,470	10,600

3.2.6 Hydrolytic Stability

The hydrolytic stability of candidate foams was measured per MIL-P-16923G using the compressive strength versus time as a measure of change in this environment. The appropriate number of free-foamed cut-cube specimens were subjected to two test environments: 23°C at 50% RH; and 71°C at 90% RH. Five samples were randomly selected at 0, 28, 56, 84, and 120-day intervals and the compressive strength measured per ASTM-D-1622. Table VIII shows the results obtained against the requirement of less than a 10-percent reduction in properties throughout the 120-day test period.

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4. Brenden, R.J., "Handbook of Foamed Plastics," Lake Publishing Corp. 1965

TABLE VIII. HYDROLYTIC STABILITY OF CHEMICALLY BLOWN FOAMS

	Compressive Strength, psi, for:							
	Chemetics CSI-740		Cook Coro-foam 589		Formulated Resins PR 2028		Witco Isofoam PE-18	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	645	645	750	750	130	130	700	700
28 days	600	675	730	760	118	148	760	780
56 days	610	640	780	730	134	128	740	790
84 days	675	710	800	800	110	140	790	730
120 days	675	700	820	820	130	140	760	820
Total Change, %	+4.7	+8.5	+9.3	+9.3	0	+7.7	+8.6	+17.0

An analysis of the data shows that the compressive strengths of the samples increased rather than decreased during the test. All samples, with the exception of Witco Isofoam PE-18, retained properties with less than a 10-percent change during the test period. A plot of the data (Figure 2) showed some variance during the test period, possibly due to a slight variation in density of the various specimens.

3.2.7 Summary

Based on the tests conducted in this phase, the Cook Coro-foam 589 appeared to be the top candidate for further evaluation. It has the shortest demold time, a relatively longer working time, a glass transition temperature greater than 71°C, density close to the Witco Isofoam PE-18's, and good compressive strength and hydrolytic stability.

3.3 Syntactic Foams

The syntactic foams evaluated are one- or two-component epoxy systems containing hollow glass spheres resulting in an overall specific gravity near 0.8. The advantage obtained is a low-density encapsulant with a moderate to high flexural strength to support the circuitry in high-shock-load environments. Since these systems are based on epoxy technology, the two-component materials can be rapidly cured with either temperature or catalysts. The single-component system considered has a cure temperature of 165°F and an extended cure time of 16 hours, but does offer savings in equipment and inspection.

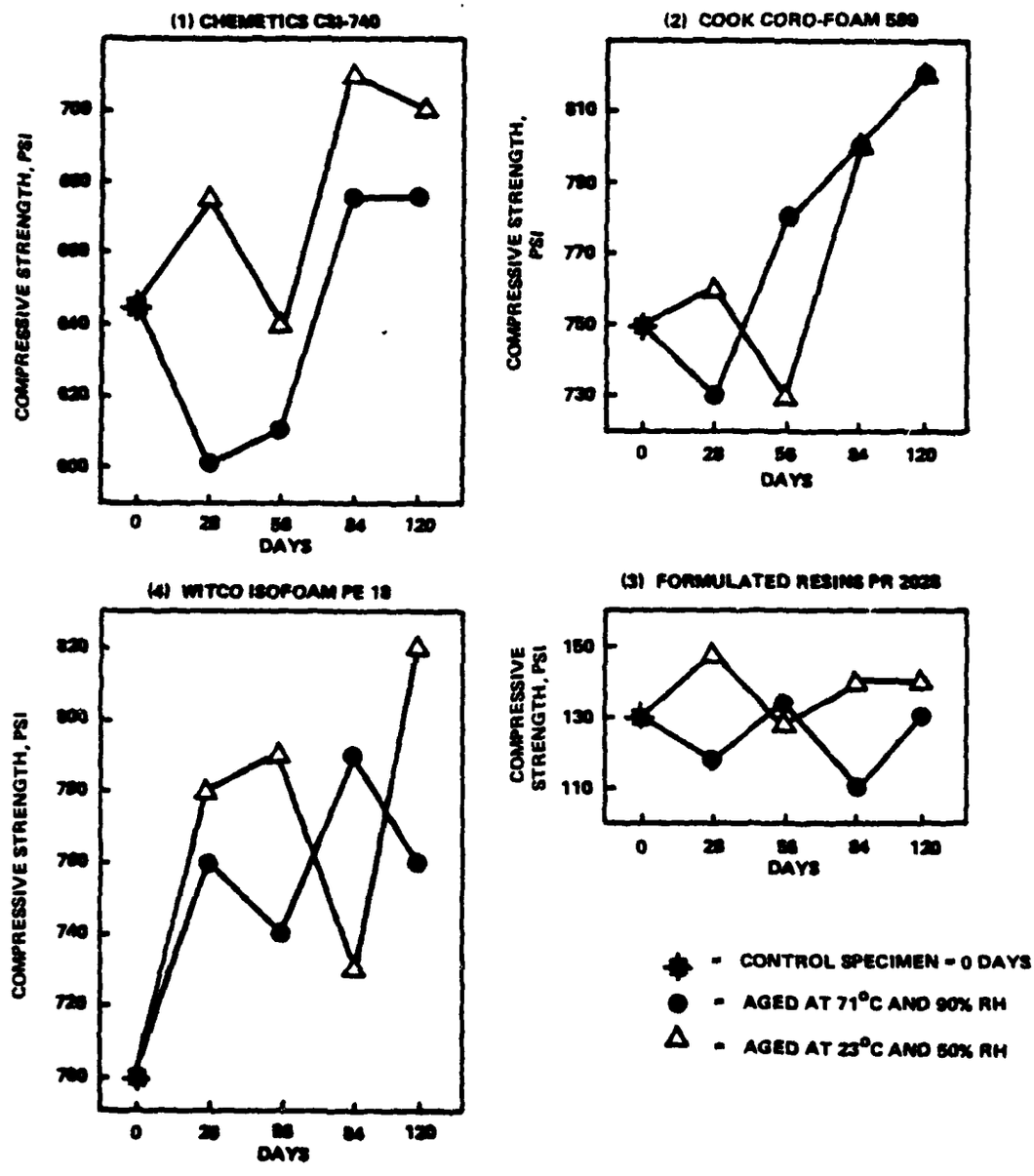

Figure 2. Hydrolytic stability results.

3.3.1 Handling Evaluation and Identification

Initial observations were made by evaluating the handling characteristics of the four candidates: three two-component and one single-component syntactic foams. The observations included the viscosity, mix ratio, filler settling, and miscibility of the components, as well as the processing temperatures and demold times. An infrared scan was made of each component to compare with subsequent samples.

Table IX summarizes this evaluation. The handling characteristics for the two component systems reveal no obvious problems, with the exception of the filler settling with the LN79055 sample. All of the samples can be handled at less than 65°C for an initial period through demolding, followed by a subsequent room temperature cure outside of the tooling. This preliminary demold time was determined on a 50-gram sample cast into a mold-released aluminum weighing dish. The demold time was determined as the time at 65°C in which the sample could be removed without damage. All of the two-component systems are epoxy-based with a hollow microsphere filler. This evaluation was done without additional catalysts. The full cure noted reveals that the materials would achieve a full cure at room temperature, or could be cured more rapidly with increased temperatures or additional catalysts.

TABLE IX. HANDLING EVALUATION OF SYNTACTIC FOAMS

	Two-Component			Single-Component
Parameter	Formulated Resins PR-2036	3M XR5090	Emerson and Cuming LN-79055	Hysol NB-509-70-2
Mixed viscosity, cps	15,000	19,000	40,000	14,000
Mix ratio	1:2	7:3	3.5:1	N/A
Filler settling	Minimum	Mininum	High	Minimum
Preheat temperature, °C	65	65	65	74
Cure temperature, °C	65	65	65	74
Demold time, min/°C	45/65	75/65	15/65	60/74
Full cure time, hr/°C	16/23 or equivalent	48/23 or equivalent	16/23 or equivalent	16/74
Handling	Good	Excellent	Poor	Good
Specific gravity	0.845	0.871	0.744	0.848

The Hysol NB-509-70-2 single component syntactic epoxy has a demold time of 1 hour at 74°C, and requires a total of 16 hours at 74°C to achieve a full cure. A storage life of 6 months at 4°C is predicted, including several days

at 23°C. An extended shelf life can be obtained by procuring this material as two components and preblending within weeks of use.

3.3.2 Flexural Properties

Samples of candidate materials were prepared in ½ x ½ x 6 in. bars cast individually. All two-component samples were cured 6 hours at 65°C to ensure a full cure. The single-component samples were cured 16 hours at 74°C. Following demolding, the samples were aged for 7 days at 23°C and 50% RH.

The flexural strength and modulus were tested on a Tinius Olson Universal Test Machine at a rate of 0.05 inches per minute on a 4-inch span per ASTM-D-790. The work-to-break was calculated from the area under the flexural stress/strain curve and was used as a measure of toughness.

Table X shows the results obtained on the candidate syntactic foams. Of these materials, the single component material has the highest flexural strength and a significantly higher combination of work-to-break and flexural modulus. The LN79055 appears brittle based on the low work-to-break values. Both the XR5090 and the LN79055 had significantly lower compressive strengths than the other materials.

TABLE X. FLEXURAL PROPERTIES OF SYNTACTIC FOAMS

	Two-Component Foam			One-Component Foam
Parameter	Formulated Resins PR 2036	3M XR5090	Emerson and Cuming LN79055	Hysol NB-509-70-2
Flexural strength, psi	7,150	3,650	3,820	9,960
Flexural modulus, psi	3.1×10^5	1.6×10^5	4.5×10^5	4.4×10^5
Work-to-break, in.-lb/in.^{2}	42.7	26.9	7.06	62.6

3.3.3 Thermal Expansion and Glass Transition Temperature

The coefficient of thermal expansion and the glass transition temperature were determined on a piece of flexural specimen using a Perkin-Elmer Thermo-mechanical Analyzer (TMA), Model TMS-1, at a scan rate of 10°C per minute. Table XI shows the coefficient of thermal expansion below the glass transition temperature. The values obtained are near those expected for these materials, with the exception of PR 2036, which seems low. The glass transition

temperature was obtained as the point at which the thermal expansion rate changed. Table XI shows that the T_g is above 71°C for all samples.

TABLE XI. THERMAL EXPANSION AND GLASS TRANSITION TEMPERATURE OF SYNTACTIC FOAMS

	Two-Component Foam			One-Component Foam
Parameter	Formulated Resins PR 2036	3M XR5090	Emerson and Cuming LN79055	Hysol NB-509-70-2
CTE, in./in./°C	29.6×10^{-6}	88.8×10^{-6}	59.1×10^{-6}	72.9×10^{-6}
T_g, °C	+76	+107	+181	+83

3.3.4 Peak Exotherm and Embedment Stress

During the initial cure of epoxy resins, an exotherm is generated from the heat of reaction. When electronics are encapsulated, the control of this exotherm is important in larger castings since it creates additional heat and residual stress on the components. A thermocouple was placed near the center of a 150-ml sample and the material exposed to the normal cure temperature. The peak exotherm was obtained by recording the temperature profile through the cure cycle and identifying the maximum temperature reached.

By adding a thermometer along with the thermocouple, the embedment stress can be obtained. This test per ASTM-F-135 correlates stress with the rise in the thermometer mercury. Each difference of 1°F between the thermometer and thermocouple readings translates to 90-psi pressure on the mercury bulb. Figure 3 shows this test setup.

The sample, thermocouple, and thermometer were placed in a 150-ml beaker. Table XII shows the peak exotherms measured. The PR 2036 and NB-509-70-2 reached exotherms greater than 150°C, breaking the thermometer bulbs. Additional samples were prepared in a 100-ml beaker in which the peak exotherm was lowered. The XR5090 showed only a minor increase over the cure temperature. The LN79055 was not tested.

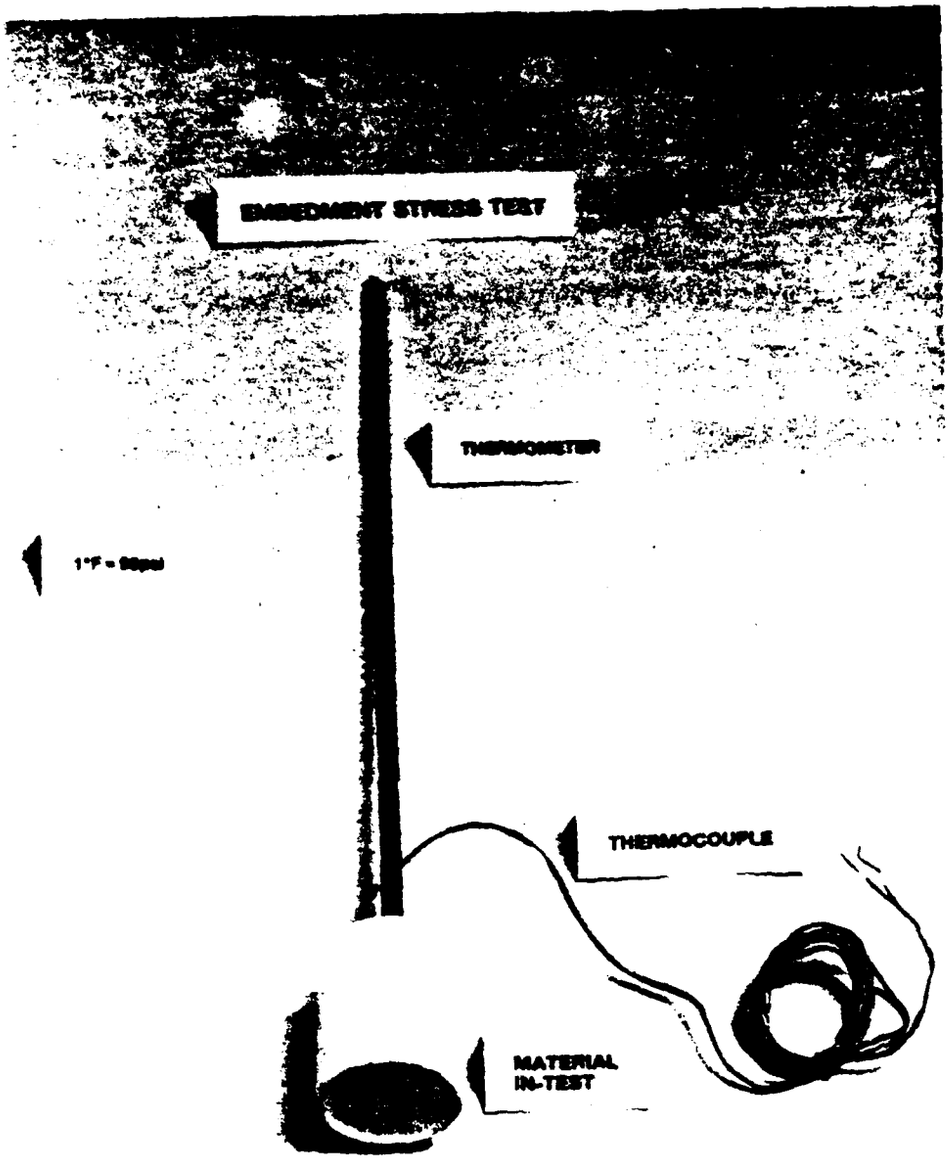

Figure 3. Embedment stress test setup.

TABLE XII. PEAK EXOTHERM OF SYNTACTIC FOAMS

Parameter	Two-Component Foam		One-Component Foam
	Formulated Resins PR 2036	3M XR5090	Hysol NB-509-70-2
Cure temperature	23°C	23°C	74°C
150-ml beaker	163°C	46°C	198°C
100-ml beaker	115°C	N/A	162°C

These results indicate that a period of time should be allowed for the peak exotherm to pass before higher temperatures are applied. The peak exotherm, however, is very mass sensitive and is also capable of being decreased by the heat sink in the tooling. In small-volume encapsulations, the peak exotherm is controllable.

After a full cure, the samples were subjected to several temperatures between -40°C and +49°C to measure the embedment stress. The difference between the thermometer and thermocouple was measured at various stabilized temperatures, and corresponding stress levels calculated. This data is plotted in Figures 4 and 5.

3.3.5 Thermal Shock

Samples were prepared and thermal shock tests conducted per MIL-I-16923G. The test involved encapsulating a 1-in.-long, 3/4-in., cold-drawn, low-carbon-steel, hexagonal-shaped bar with the plastic. The result was a one-inch diameter, cylindrical specimen. The sample was then thermal shocked between -55°C and +130°C for 10 cycles. An inspection for cracks is made after each cycle. If four of five samples of a material pass all 10 cycles without cracking, then the material has passed the test.

This test shows the ability of a material to withstand a differential thermal expansion stress. The plastic, having a large CTE in comparison to the steel insert, creates alternating expansion and contraction forces. Brittle materials traditionally fail this test.

The PR 2036 and XR5090 passed the 10 cycles in five out of five samples. The NB-509-70-2 passed in 4 out of 5 samples, while the LN79055 failed 5 out of 5 samples.

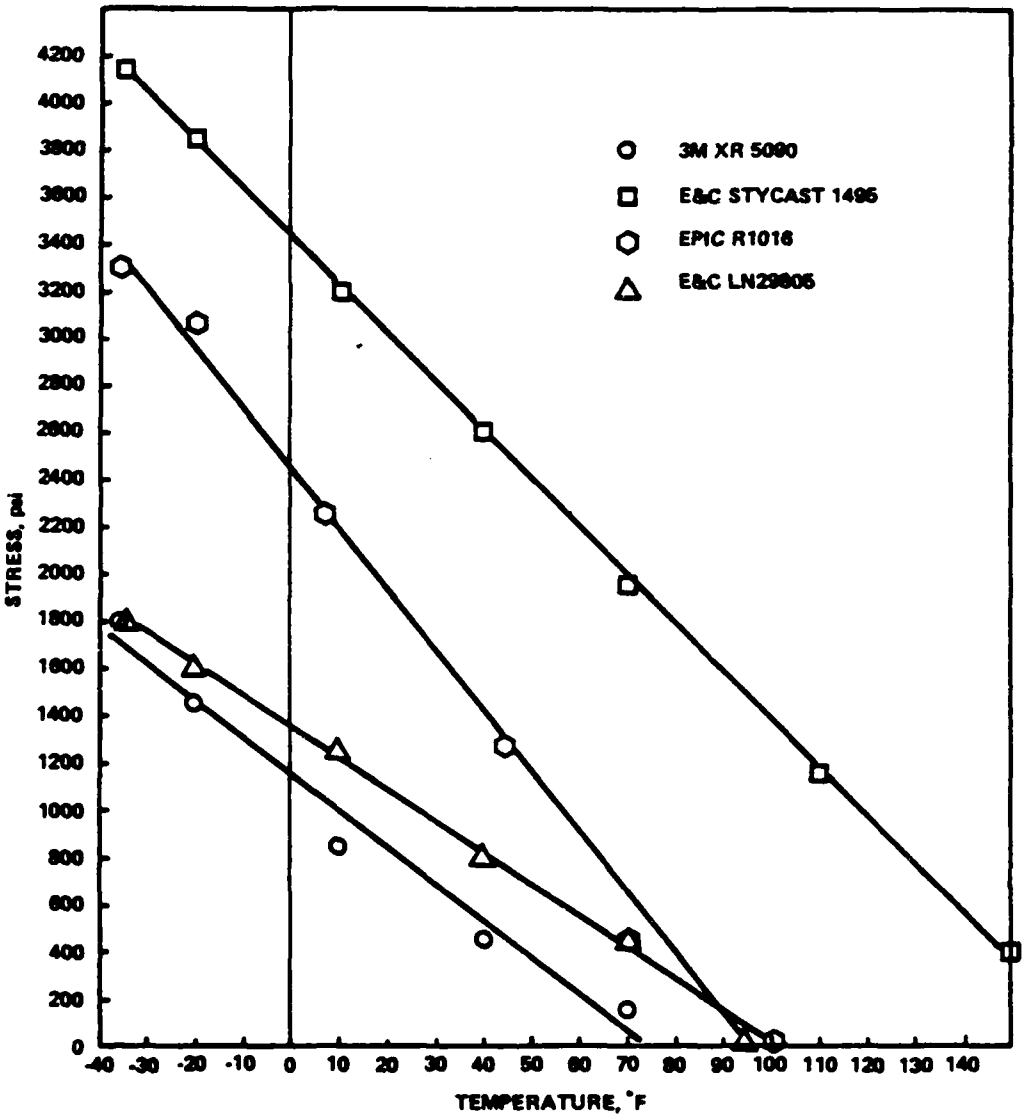

Figure 4. Embedment stress test results (150-ml beaker).

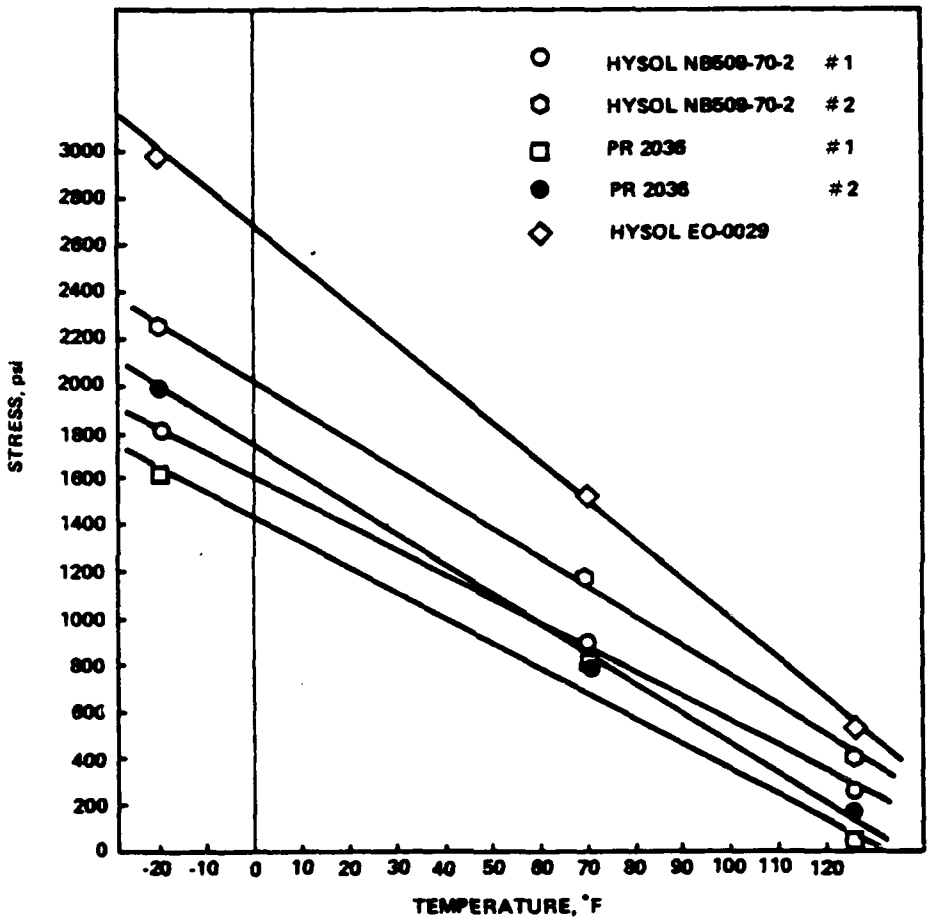

Figure 5. Embedment stress test results (100-ml beaker).

3.3.6 Tensile Shear Adhesion

The adhesion of the candidate materials was measured by tensile shear per ASTM D-1002. Specimens were prepared on 2024 aluminum substrates. The substrates were prepared by vapor degreasing in trichloroethylene followed by sandblasting with aluminum oxide #3 media and a final degreasing. The candidate material was applied to both mating surfaces of the tensile shear substrates, racked and cured under 50 psi spring pressure. A bond line of approximately 0.005 in. was obtained. The two-component specimens were cured 6 hours at 65°C while the single-component specimens were cured 16 hours at 74°C. Following the cure cycle, the specimens were aged for 7 days at 23°C and 50% R.H. prior to testing.

The specimens were tested on a Tinius Olson Universal Test Machine at 0.05 inches per minute travel until failure. The two-component materials, PR2036, XR5090, and LN79055, achieved average values of 2580, 2160, and 1900 psi respectively. The single-component NB509-70-2 achieved a value of 700 psi average tensile shear strength, which is low for an encapsulant.

3.3.7 Hydrolytic Stability

Samples were prepared for hydrolytic stability tests per MIL-I-16923G. Shore hardness was tested periodically throughout the 120-day test period. Table XIII and Figure 6 show that all materials passed this test with less than a 10 percent reduction in hardness.

TABLE XIII. HYDROLYTIC STABILITY OF SYNTACTIC FOAMS

	Shore D Hardness of:							
	Two-Component Foam						One-Component Foam	
	Formulated Resins PR-2036		3M XR-5090		Emerson and Cuming LN-79055		Hysol NB-509-70-2	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	84D	84D	79D	79D	81D	81D	85D	85D
28 days	85D	85D	80D	81D	81D	82D	85D	86D
56 days	85D	85D	80D	84D	81D	82D	85D	85D
84 days	85D	85D	80D	85D	81D	82D	84D	85D
120 days	85D	85D	80D	84D	81D	82D	85D	83D
Total Change, %	+1.2	+1.2	+1.3	+6.0	0	+1.2	0	-2.4

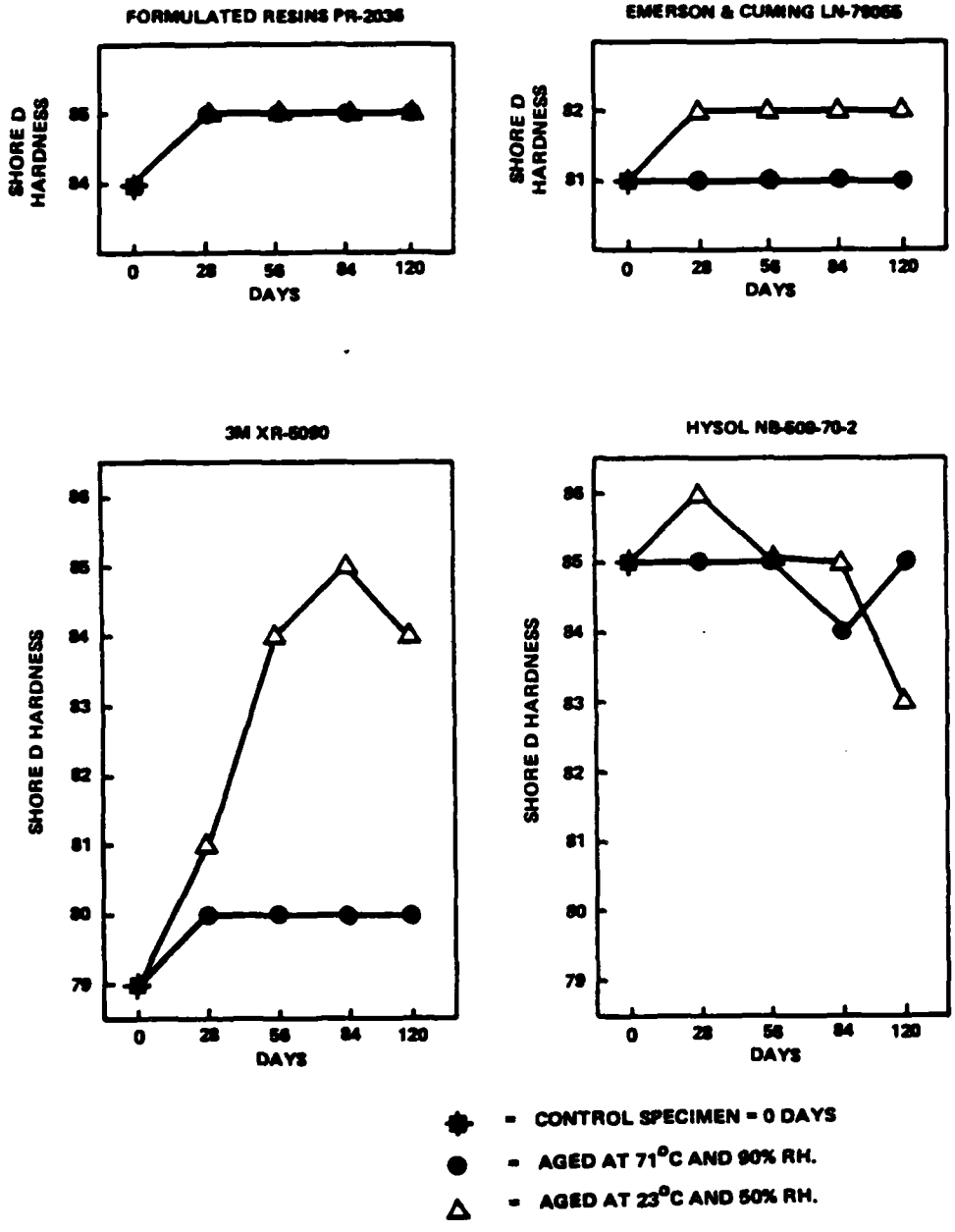

Figure 6. Hydrolytic stability test results (syntactic foams).

3.3.8 Summary

An analysis of the tests on the syntactic foam materials indicated that the top candidates for further evaluation were Formulated Resins PR2036 and Hysol NB-509-70-2. These are the highest strength samples and have passed all evaluations. They do possess a high peak exotherm which must be monitored. The 3M XR5090 has also passed the tests and has a minimum exotherm, but has much lower flexural properties.

3.4 Rigid Filled Epoxy Compounds

Filled epoxy encapsulants are widely used in electronic encapsulation, particularly in medium to high-shock environments. This family of materials consists of an epoxy resin and hardener and contains a silica, sand, or mineral reinforcement, and usually a reactive diluent to improve flow. Long cure times at elevated temperatures are typically required.

The filled systems selected for this evaluation are both one- and two-component systems. The two-component systems may be accelerated in curing by increasing temperatures or by adding catalysts. The one-component material has an extended cure time at an elevated temperature, but does have advantages in reduced equipment and inspection requirements.

3.4.1 Handling Evaluation and Identification

Initial evaluations of these candidates involved their handling characteristics including viscosity, mix ratio, filler settling, process temperatures, and demold times. An infrared scan was made of each component for general identification and for future reference.

Table XIV summarizes the observations in this phase of the evaluation. The viscosities of these materials decrease significantly at the 65°C processing temperature. The viscosity of the single-component E0-0029 at room temperature is very high, making handling difficult. At elevated temperatures, however, handling is significantly improved. The mix ratio of Stycast 1495 and R1016 are unbalanced, but still easily handled in automated meter-mix equipment. The demold times of the candidate materials show that they cannot be rapidly removed from tooling in a 50-gram batch. No filler settling problems were noted in the samples.

TABLE XIV. HANDLING EVALUATION OF FILLED EPOXY

Parameter	Two-Component Epoxy			One-Component Epoxy
	Emerson and Cuming LN-79054	Emerson and Cuming Stycast 1495/Catalyst 9	Epic R1016	Hysol EO-0029
Mixed viscosity at 23°C, cps	25,000	21,000	4,500	112,000/23°C 9,100/74°C
Mix ratio	5.2:1	100:4	100:3.3	N/A
Filler settling	Minimum	Minimum	Minimum	Minimum
Preheat temperature, °C	65	65	65	74
Cure temperature, °C	65	65	65	74
Demold time, min/°C	25/65	30/65	25/65	75/74
Full cure time, hr/°C	6/65	1/65	4/65	16/74
Specific gravity	1.77	1.87	1.73	1.73
Handling	Good	Good	Good	Fair

3.4.2 Flexural Properties

Test samples were prepared by preheating the materials to their processing temperature, mixing and deaerating under vacuum, and casting ½ x ½ x 6 in. bars. All two-component samples were cured for six hours at 65°C to ensure full cure. The single-component sample was cured 16 hours at 74°C. Following demolding, the samples were aged for 7 days at 23°C and 50 percent R.H.

The flexural strength and modulus were tested on a Tinius Olson Universal Test Machine at a rate of 0.05-in./min crosshead speed on a four-inch span per ASTM-D-790. The work-to-break was calculated from the area under the flexural stress/strain curve and measured the toughness of the material.

Table XV shows the results obtained on the candidate filled epoxy materials. The single-component E0-0029 and two-component R1016 showed the highest strength and work-to-break. All of the materials had an excellent toughness for this type of encapsulant.

TABLE XV. FLEXURAL PROPERTIES OF FILLED EPOXY

	Two-Component			One-Component
Parameter	Emerson and Cuming LN79054	Emerson and Cuming Stycast 1495/Catalyst 9	Epic R1016	Hysol E0-0029
Flexural strength, psi	10,300	12,700	16,900	16,500
Flexural modulus, psi	1.26×10^6	1.65×10^6	1.22×10^6	1.84×10^6
Work-to-break in.-lb/in.^{2}	24.4	25.6	67	35.3

3.4.3 Thermal Expansion and Glass Transition Temperature

The coefficient of thermal expansion and the glass transition temperature were determined using a Perkin-Elmer TMA at a scan rate of 10°C/min. The coefficient of thermal expansion (CTE) was recorded for temperatures below the glass transition temperature (T_g).

Table XVI shows the values obtained. The CTE for the LN79054 is higher than expected for this class of materials. The remainder of the materials exhibit a CTE near expected values. The T_g on all materials is above the +71°C requirement.

TABLE XVI. COEFFICIENT OF THERMAL EXPANSION AND GLASS TRANSITION TEMPERATURE OF FILLED EPOXY

Parameter	Two-Component			One-Component
	Emerson and Cuming LN79054	Emerson and Cuming Stycast 1495/Catalyst 9	Epic R1016	Hysol E0-0029
CTE, in./in./°C	90×10^{-6}	36×10^{-6}	43.5×10^{-6}	37×10^{-6}
T_g, °C	+91	+90	+83	+89

3.4.4 Peak Exotherm and Embedment Stress

The peak exotherms and embedment stresses were measured as described in 3.3.4. The embedment stress tests were conducted per ASTM-F-135 in a 150-ml beaker. Table XVII shows the peak exotherms measured.

TABLE XVII. PEAK EXOTHERM TEMPERATURE OF FILLED EPOXY

Parameter	Two-Component			One-Component
	Emerson and Cuming LN79054	Emerson and Cuming Stycast 1495/Catalyst 9	Epic R1016	Hysol E0-0029
Cure temperature		23°C	23°C	74°C
150 ml	Not Tested	47°C	33°C	149°C
100 ml		—	—	85°C

The Stycast 1495 and R1016 had minimum exotherms. The E0-0029, however, resulted in a high exotherm and broken thermometer when tested in 150-ml quantities. A retest was made in a 100-ml beaker.

Figures 4 and 5 show the graphs of embedment stress as a function of test temperature. The embedment stresses generated by these materials are significant, reaching well over 3,000 psi at -40°C and over 4,000 psi with the Stycast 1495.

3.4.5 Thermal Shock

Samples were prepared and the tests conducted per MIL-I-16923G as described in 3.3.5. After the 10-cycle test from +130°C to -55°C, only two of the candidates passed. Four of five Stycast 1495 samples and all five EO-0029 samples survived the test. The LN79054 and R1016 had 2 of 5 and 0 of 5, respectively, thus failing the test.

3.4.6 Tensile Shear Adhesion

Tensile shear specimens were prepared on 2024 aluminum specimens as described in section 3.3.6. The candidate materials were applied and then cured by appropriate cure cycles. The specimens were tested at a rate of 0.05 in./min at room temperature.

The values generated were 1900, 1730 and 1820 psi for the Stycast 1495, R1016, and E0-0029 respectively. The LN79054 was not tested.

3.4.7 Hydrolytic Stability

Samples were prepared and tested for hydrolytic stability tests per MIL-I-16923G. Hardness was measured periodically through the 120-day test cycle. Table XVIII revealed that several of the materials exceeded the 10 percent reduction in hardness allowable in this test. A further analysis (see Figure 7) shows that all of the samples have leveled off for two or more test periods. It does not appear that this indicates a catastrophic failure mode.

3.4.8 Summary

A review of the test results generated on the candidate filled epoxies indicates that the E0-0029 and Stycast 1495 should be evaluated further. These are the only materials which have passed the thermal shock test. The remaining properties tested indicated that they are consistent with the objectives of this program.

TABLE XVIII. HYDROLYTIC STABILITY OF FILLED EPOXY

	Barcol 934-1 Hardness for:							
	Two-Component Epoxy						One-Component Epoxy	
	Emerson and Cuming LN-79054		Emerson and Cuming Stycast 1495/Catalyst 9		Epic R1016		Hysol NB-2080-33-1	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	55	55	62	62	55	55	58	58
28 days	53	56	57	58	45	54	52	57
56 days	52	55	54	57	44	50	51	54
84 days	52	55	54	56	44	48	51	53
120 days	53	55	55	56	44	48	52	52
Total Change, %	-3.8	0	-11.3	-9.7	-20.0	-12.7	-10.3	-10.3

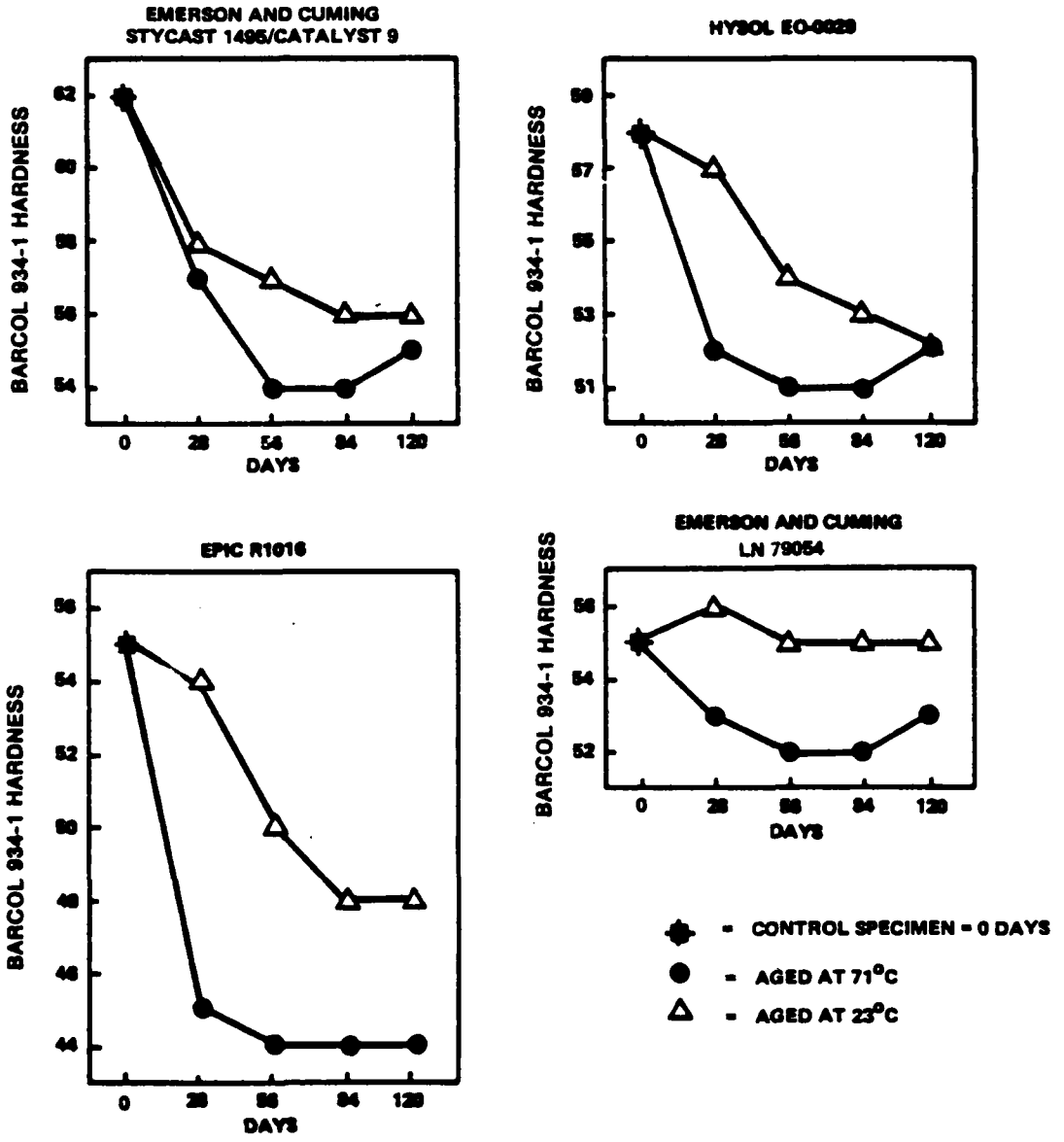

Figure 7. Hydrolytic stability test results (filled epoxy).

3.5 Semirigid Urethanes (>70D)

High hardness urethane compounds are used in electronic encapsulation in the low-to-medium shock environments. These materials typically consist of an unfilled high isocyanate content urethane prepolymer with an amine or polyol curing agent. With this chemistry, rapid reaction times result in short cure cycles. The final cure can be completed with atmospheric moisture.

3.5.1 Handling Evaluation and Identification

The preliminary evaluation of these candidates involved handling characteristics including viscosity, mix ratio, process temperatures, and demold times. An infrared scan was made of each component for reference.

Table XIX summarizes these observations. Excellent demold times were achieved with the ISP-100 and PSX-75D. The ISP-100 was used with 0.5% of stannous octoate, thus resulting in a three-component system. This ratio, arrived at by experimentation, allows sufficient working time to prepare samples. The stannous octoate can be combined with the polyol component, thus achieving a two-component system. The PSX-75D exhibited a large number of voids upon curing, even though the samples were evacuated. The EN24 requires a high cure temperature of greater than 80°C, which may cause problems with electronic hardware. The LN29805 handles well, but requires nearly one hour to demold. The mix ratios of these materials are easily accommodated by automated meter/mix equipment.

TABLE XIX. HANDLING EVALUATION OF SEMIRIGID URETHANES

Parameter	Emerson and Cuming LN-29805	Conap EN-24	Dow ISP-100	Arnco Fastcast PSX-75D
Mixed viscosity at 25 °C, cps	4500	3300	290/120°F	1500
Mix ratio	100:25.5	100:82	27:10:.5%	94:100
Preheat temperature, °C	23	23	23	32
Cure temperature, °C	65	80	23	25
Demold time, min/°C	60/65	30/82	10/23	15/65
Full cure time	2 hr/65°C	7 days/23°C or 4 hr/80°C	45 sec/100°F	7 days/23°C or 4 -6 hr/65°F
Handling	Good	Good	Good	Fair - Voids

3.5.2 Flexural Properties

Test samples were mixed at their specific process temperature, evacuated and cast into ½ x ½ x 6 in. test specimens. All test specimens were cured for 6 hours at 65°C and aged 7 days at 25°C and 50% relative humidity, except the ISP-100 which was only cured for 7 days at 23°C and a 50% relative humidity.

The flexural strength and modulus were tested at a crosshead speed of 0.05 in./min on a 4-inch span per ASTM D-790. The work-to-break was calculated from the area under the flexural stress-strain curve, and was used as a measure of material toughness.

Table XX shows the results obtained on the candidate urethanes. The ISP-100 and PSX-75D tested very high in flexural properties and toughness, while the LN29805 and EN24 were much lower.

TABLE XX. FLEXURAL PROPERTIES OF SEMIRIGID URETHANES

Parameter	Emerson and Cuming LN29805	Conap EN24	Dow ISP-100	Arnco Fastcast PSX-75D
Flexural strength, psi	3170	1210	9400	6460
Flexural modulus, psi	7.4×10^4	4×10^4	24×10^4	17×10^4
Work-to-break, in.-lb/in.^{2}	39.9	16.5	120.0	85.0

3.5.3 Thermal Expansion and Glass Transition Temperature

The coefficient of thermal expansion and the glass transition temperature was determined on a cured specimen using a Perkin-Elmer TMA at a scan rate of 10°C per minute. The thermal expansion is recorded for temperatures below the glass transition temperature.

Table XXI shows the values obtained. Of the samples tested, only the LN29805 achieved the 71°C minimum glass transition temperature requirement imposed during this evaluation. The ISP-100 at 68°C is very close and could have achieved the minimum accepted value if a higher cure temperature had been used. Both the EN24 and PSX-75D have values well within the use temperature of electronic circuitry. This can lead to significant material property changes on either side of the glass transition temperature.

The coefficients of thermal expansion are quite high when compared to the filled systems in previous sections. Care must be taken with these materials when used in electronic encapsulation to ensure that these higher thermal expansion rates are compatible with the electronic assembly.

TABLE XXI. THERMAL EXPANSION AND GLASS TRANSITION TEMPERATURE OF SEMIRIGID URETHANES

Parameter	Emerson and Cuming LN29805	Conap EN24	Dow ISP-100	Arnco Fastcast PSX-75D
T_g, °C	+81	+12	+68	+44
CTE, in./in./°C	167×10^{-6}	125×10^{-6}	82.4×10^{-6}	77×10^{-6}

3.5.4 Peak Exotherm and Embedment Stress

The peak exotherm and embedment stress tests were performed as described in Section 3.3.4. Table XXII shows the peak exotherms measured in 150 and 100-ml beakers. Only the LN29805 and ISP-100 candidates were tested because of the previous data of glass transition temperature.

TABLE XXII. PEAK EXOTHERM OF SEMIRIGID URETHANES

Parameter	Emerson and Cuming LN29805	Conap EN24	Dow ISP-100	Arnco Fastcast PSX-75D
Cure temperature	65°C	Not Tested	23°C	Not Tested
150-ml	127°C		129°C	
100-ml	--		131°C	

The LN29805 showed a 127°C exotherm when cured at 65°C. The ISP-100 showed high exotherms of about 130°C when cured at 23°C. The exotherm did not change when the material quantity was reduced to 100-ml.

Figure 4 shows the embedment stress curve for LN29805. Values of up to 1800 psi were obtained at -40°C. This is a significant reduction from the syntactic and filled epoxy systems. The thermometers for the ISP-100 did not function in either the 150 or 100-ml beakers.

3.5.5 Thermal Shock

Samples were prepared and tested per MIL-I-16923G, as described in Section 3.3.5. After the 10-cycle test, only the EN24 and ISP-100 passed, with 5 of 5 samples completing the test without visual damage. The LN29805 failed, with 1 of 5 surviving, while the PSX-75D failed with 0 of 5 surviving the test.

3.5.6 Tensile Shear Adhesion

Tensile shear specimans were prepared on 2024 aluminum substrate using the procedures described in Section 3.3.6. Values of 1430, 1820, 690, and 1250 psi were measured on LN29805, EN24, ISP-100, and PSX-75D, respectively. The value measured on the ISP-100 is considered low for this type of material.

3.5.7 Hydrolytic Stability

Samples were prepared and tested for hydrolytic stability per MIL-I-16923G. Shore hardness was measured periodically throughout the 120-day test cycle. Table XXIII shows that the EN24 increased significantly in hardness through the first 28 days, indicating incomplete cure, but then stabilized through the remaining test period. The requirement is for no more than a 10 percent reduction in hardness. All of the candidates showed very stable results in this test. Figure 8 shows the plot of this data.

TABLE XXIII. HYDROLYTIC STABILITY OF SEMIRIGID URETHANES

	Shore D Hardness of:							
	Emerson and Cuming LN 29805		Conap EN- 24		Dow ISP-100		Arnco Fastcast PSX-75D	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	72D	72D	64D	64D	79D	79D	76D	76D
28 days	73D	76D	71D	72D	80D	79D	77D	76D
56 days	72D	72D	71D	72D	78D	79D	76D	76D
84 days	72D	72D	72D	71D	78D	78D	75D	77D
120 days	72D	73D	73D	72D	78D	78D	76D	79D
Total Change, %	0	+1.4	+14.1	+12.5	-1.3	-1.3	0	+4.0

3.5.8 Summary

A review of the test results generated on the candidate semirigid urethanes reveal that the ISP-100 comes the closest to meeting the objectives. The deviations in T_g and low adhesion values, along with a high exotherm, are not prohibitive problems in the size (resin volume) of the electronic encapsulation planned in this program. The remaining materials were dropped from further testing.

3.6 Elastomers (<70D)

Castable elastomers are currently used in electronic encapsulation for devices experiencing low shock requirements. These materials are typically unfilled or contain a low percentage of fillers. The candidates selected in this program are three unfilled urethane compounds which are polyol cured. The Uniroyal B635 is a medium hardness material while the Castall and Hysol candidates are low hardness compounds. These materials are lower isocyanate

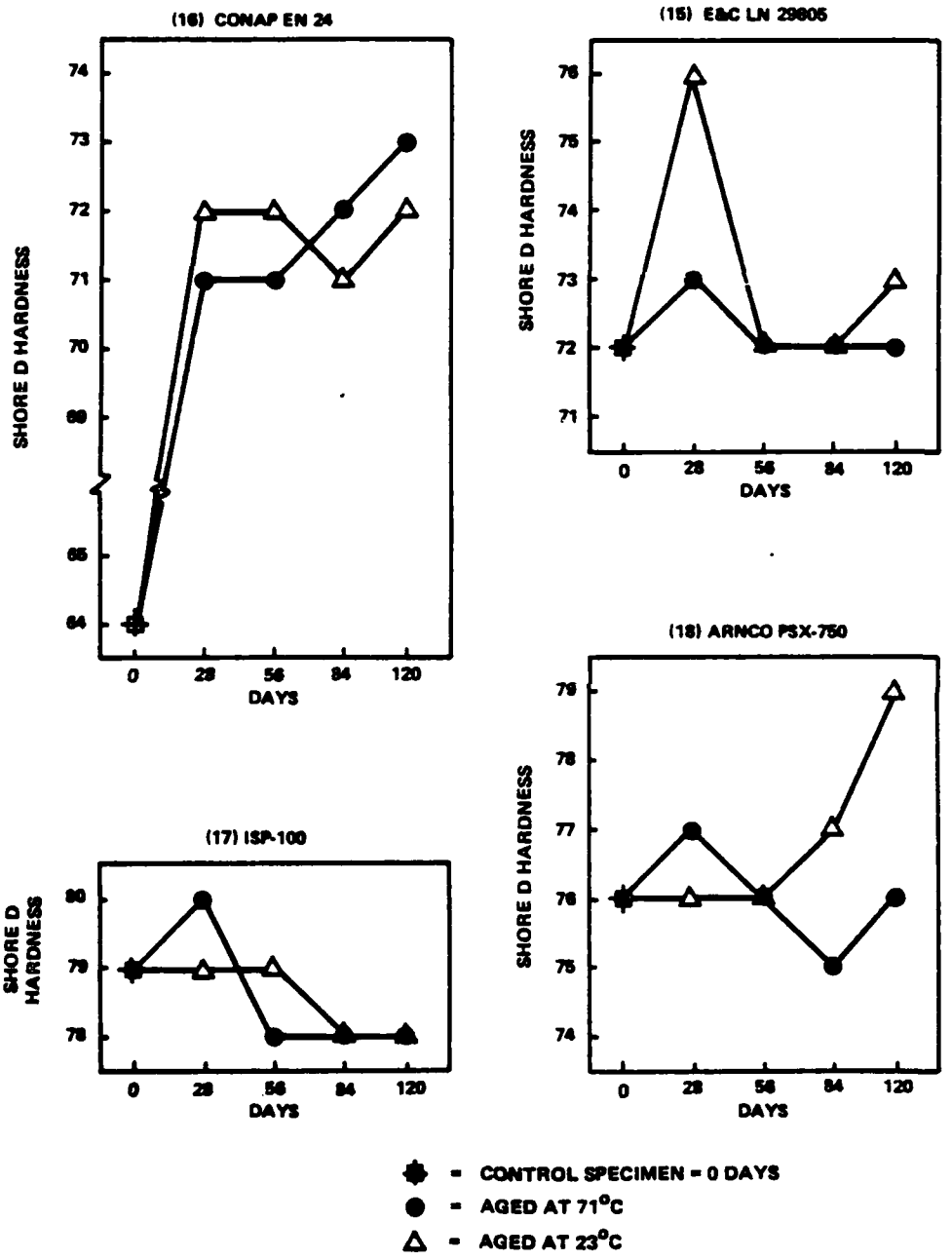

Figure 8. Hydrolytic stability test results (semirigid urethanes [> 70 D]).

content prepolymers than those tested in Section 3.5. They can be accelerated with temperature or the addition of catalysts.

3.6.1 Handling Evaluation and Identification

The handling properties of the candidate elastomers were evaluated by characterizing the viscosities, mix ratios, process temperatures, and demold times. An infrared scan was obtained on each component to ensure that the candidates were not identical and for future reference.

Table XXIV summarizes the results of the preliminary evaluation. The B635 was found to require the shortest demold time but does have significant preheat requirements to ensure miscibility of the components. The CU-2008 and NB2090-26 require at least 2 hours at temperature to demold. All of the candidates will achieve full cure after 7 days at room temperature, or can be accelerated by temperature or additional catalysts. The mix ratios are compatible with automated meter/mix equipment.

TABLE XXIV. HANDLING EVALUATION OF ELASTOMERS

Parameter	Uniroyal B635/1,4 BD	Castall CU-2008	Hysol NB2090-26
Mixed viscosity at 25°C, cps	1500/60°C	5000	2600
Mix ratio	100:7.9	22:10	100:60
Preheat temperature, °C	Part A 82 Part B 60	23	23
Cure temperature, °C	23	23	23
Demold time, hr/°C	0.5/79	2.0/65	2.0/79
Full cure time	7 days/23°C or 1 hr/110°C	7 days/23°C	7 days/23°C or 16 hr/79°C
Handling	Fair	Good	Good
Isocyanate Type	MDI	MDI	MDI

3.6.2 Tensile Properties

Samples were prepared and cured 16 hours at 79°C for B635 and NB2090-26 and 16 hours at 65°C for CU-2008 materials. Specimens were cut from 6 x 6 x 0.125-in. sheets. Tensile and elongation were tested per ASTM-D-412. Tests were run at -40°C, 23°C, and 71°C to measure the changes in properties versus temperature. The tensile strength at 100% elongation was recorded (100% modulus).

Table XXV shows the tensile property results obtained. The B635 shows the least change in properties versus temperature, but still experiences nearly a threefold change in tensile strength and modulus from -40°F to +71°C. The CU-2008 and NB2090-26 showed nearly a 19-times and 7-times change, respectively. The elongation of the materials changed much less dramatically. The CU-2008 has a very low tensile strength at 71°C, making its use questionable in this application.

TABLE XXV. TENSILE PROPERTIES OF ELASTOMERS

Parameter	Uniroyal B635/1,4 BD	Castall CU-2008	Hysol NB2090-26
Tensile strength, psi, at			
-40°C	5,330	2,570	3,700
23°C	3,620	770	960
71°C	1,830	135	520
Elongation, %, at			
-40°C	410	500	210
23°C	550	370	240
71°C	460	230	120
100% modulus, psi, at			
-40°C	2,450	1,060	2,180
23°C	1,360	230	450
71°C	920	70	410

3.6.3 Glass Transition Temperature (T_g)

The T_g was measured on a cured specimen using a Perkin-Elmer TMA at a scan rate of 10°C per minute. The T_g of elastomers is below room temperature. Since the goal of an encapsulant is to have the T_g outside of the operating temperature of the device in which it is used, the T_g should then be less than -40°C.

The results obtained showed the B635 has a T_g of -39°C, the CU-2008 of -58°C, and the NB2090-26 of -43°C. The B635 value is close enough to the requirement that all the candidates considered meet this test.

3.6.4 Peel Strength

Peel strength tests were run by casting a 0.125-in. thickness of material onto a cleaned 1 by 3 in. piece of G-10 glass epoxy circuit board material. The G-10 board was prepared by etching off a copper-clad surface followed by solvent cleaning with trichloroethylene. A 180° peel test was conducted per ASTM-D-903 at a crosshead speed of 12 in./min. The samples were cut back to the substrate to promote adhesive failure.

The results show the B635 has the highest peel strength at 17 lb/in. of width, followed by CU-2008 at 7.6 lb and the NB2090-26 at 1.0 lb. While this is a severe test for adhesion, the NB2090-26 value is still considered undesirably low.

3.6.5 Thermal Stability

Samples of the candidates were placed in a 71°C air circulating oven and their changes in hardness were measured periodically up to 1000 hours. Table XXVI shows that the only significant change was found with CU-2008.

TABLE XXVI. THERMAL STABILITY OF ELASTOMERS

Length of Aging at 71°C	Heat Stability, Shore Hardness Change:		
	Uniroyal B635/1,4 BD	Castall CU-2008	Hysol NB2090-26
0 hours	41D	60A	56A
100 hours	40D	64A	57A
200 hours	41D	67A	55A
500 hours	43D	69A	59A
1,000 hours	42D	72A	60A

3.6.6 Hydrolytic Stability

Samples were prepared and tested for hydrolytic stability per MIL-I-16923G. Hardness was monitored periodically through the 120-day test. Table XXVII shows that only the CU-2008 showed a significant change in properties. This change was an increase in hardness rather than a reduction for which a failure is recorded. Figure 9 shows a plot of this data.

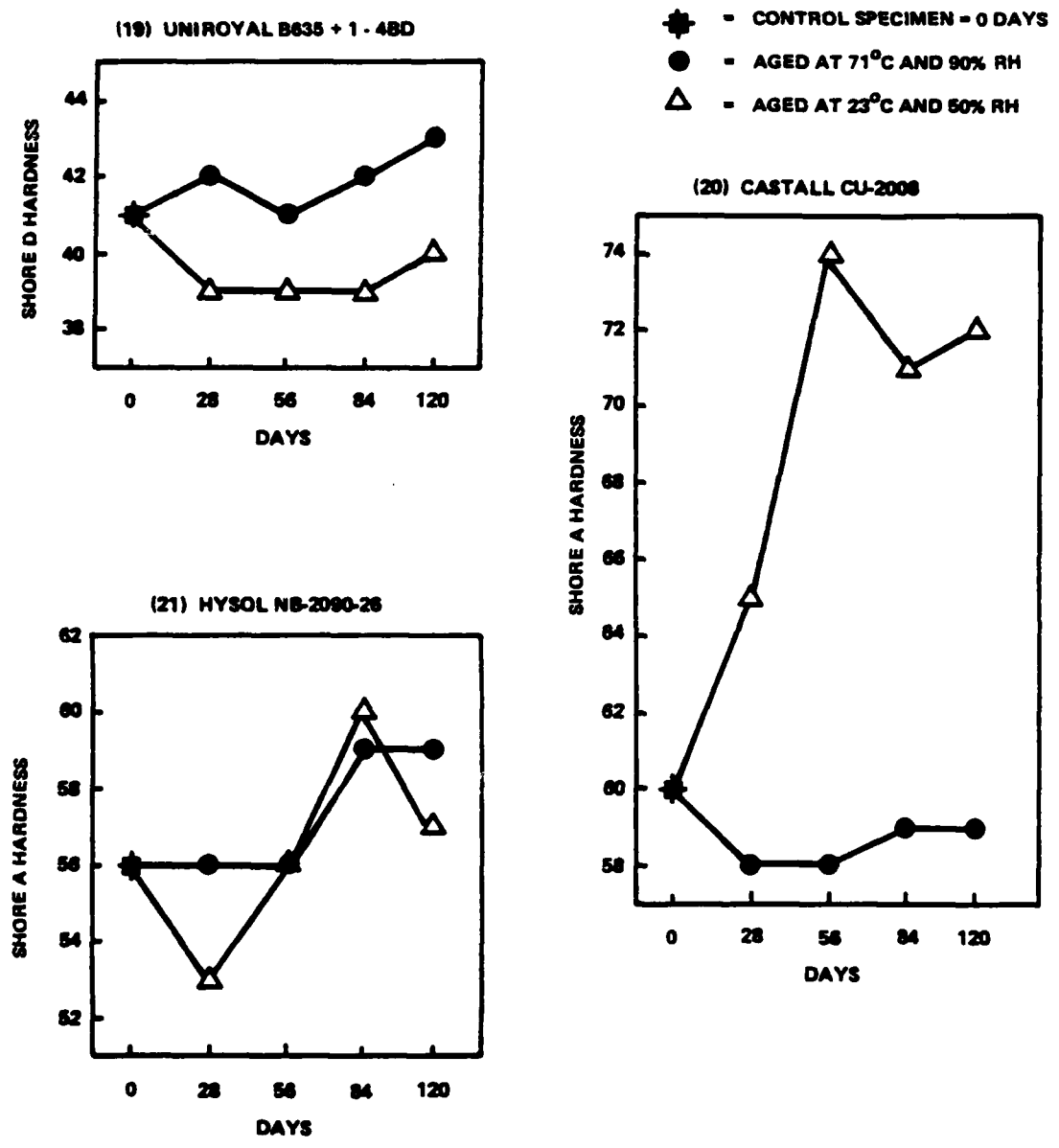

Figure 9. Hydrolytic stability test results (castable elastomers [<70 D]).

TABLE XXVII. HYDROLYTIC STABILITY OF ELASTOMERS

	Shore Hardness of:					
	Uniroyal B635/1,4 BD		Castall CU-2008		Hysol NB2090-26	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	41D	41D	60A	60A	56A	56A
28 days	42D	39D	58A	65A	56A	53A
56 days	41D	39D	58A	74A	56A	56A
84 days	42D	39D	59A	71A	59A	60A
128 days	43D	40D	59A	72A	59A	57A
Total Change, %	+4.9	-2.4	-1.7	+20	+5.4	+1.8

3.6.7 Summary

Based on a review of the test data generated in this phase, only the Uniroyal B635 cured with 1,4 Butanediol was recommended for further evaluation. Both the Castall and Hysol materials had longer demold times and greater changes in properties versus temperature.

3.7 Injection Molded Compounds

Injection molded plastics are currently used in the manufacturing of electrical components, but not in the encapsulation of electronic circuitry. This is partially due to the higher temperature and pressure environments involved in these processes. (See Section 2.2 for a further discussion.)

One method of low-pressure injection molding is the utilization of structural thermoplastic foams. These require only a partial fill of the cavity, followed by the action of a blowing agent to expand the material. Cycle times are slightly longer than typical for thermoplastic injection molding, but are still in the range of 1 to 5 minutes. A foamed thermoplastic polyurethane material, Uniroyal E80, was selected for evaluation based on our previous experience. It had demonstrated good low-temperature performance and a low-processing temperature of 205°C. A level of blowing agent (LNP Foamkon 23) was used that resulted in a 30% void volume. Tests were then performed as discussed in the following sections.

3.7.1 Demold Times

Samples of Uniroyal E80 with blowing agent were injection-molded at 205°C. A partial shot was introduced into the cavity, allowing the blowing agent to expand and produce a 30% void volume. A specific gravity of 0.97 was achieved. A demold time of five minutes was needed to remove a ½ x ½ x 6-in. test bar without either distortion or serious imprint from the knock-out pins.

3.7.2 Glass Transition Temperature (T_g)

The T_g was measured on a Perkin-Elmer TMA at a scan rate of 10°C per minute. A measurement of -46°C was based on the inflection point in the slope of thermal expansion. This is satisfactorily outside of the restricted range recommended in this program.

3.7.3 Compressive Properties

One-inch long samples were cut from the ½ x ½ x 6-in. bars. Tests were conducted per ASTM-D-695 at a test speed of 0.05 inches of crosshead speed per minute. The data were recorded for tests run at -40°C, 23°C, and 71°C. Table XXVIII shows the values measured for compressive strength and modulus versus temperature. Although it is not a high-strength material, E80 does retain a reasonable amount of its compressive properties versus temperature.

TABLE XXVIII. COMPRESSIVE PROPERTIES OF THERMOPLASTIC FOAM (UNIROYAL E80)

	Test Temperature		
Parameter	-40°C	+23°C	+71°C
Compressive strength, psi	260	158	108
Compressive modulus, psi	2500	1560	1370

3.7.4 Hydrolytic Stability

Samples were submitted for hydrolytic stability tests per MIL-I-16923G using the compressive strength as a measure of change versus time in the 120-day test environment. The appropriate number of ½ x ½ x 1-in. specimens were prepared and subjected to the two environments: 23°C at 50 percent RH; or 71°C at 90 percent RH. Five specimens were randomly selected at 0, 28, 56, 84, and 120-day intervals, and their compressive strengths measured per ASTM-D-695.

Table XXIX shows the results obtained. The requirement is for less than a 10-percent reduction in properties throughout the 120-day test period. Figure 10 shows a graph of the data. A gradual increase in strength was observed

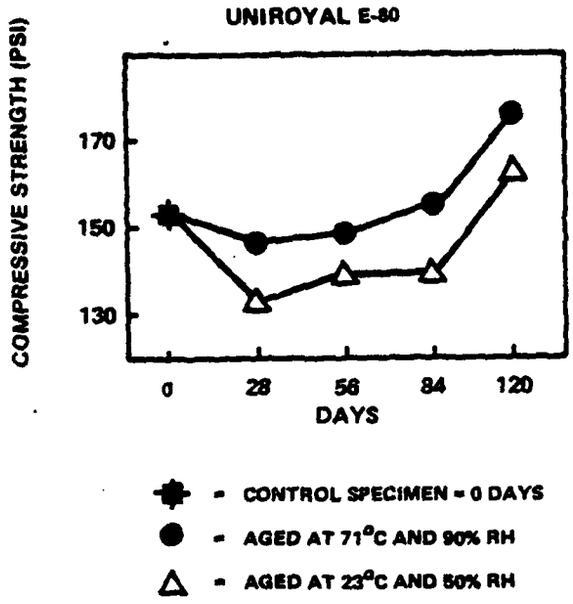

Figure 10. Thermoplastic foam (Uniroyal E-80) hydrolytic stability.

throughout the test period, indicating some changes are occurring in the specimens. The values are low enough, however, that a 10% change in values may be within the accuracy of the test.

TABLE XXIX. HYDROLYTIC STABILITY OF THERMOPLASTIC FOAM (UNIROYAL E80)

	Compressive Strength, psi	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	153	153
28 days	146	133
56 days	148	139
84 days	155	139
120 days	176	163
Total Change, %	+15	+6.1

3.7.5 Summary

Based on a review of the data measured, the Uniroyal E80 in a foamed condition does achieve the short demold time objective. The process temperature of 205°C was the lowest that was achieved, but is considerably higher than the 71°C maximum-use temperature of ordnance electronics. The effect of this thermal shock on the electronics has not been evaluated here. The compressive properties, while not high, are relatively stable through the use temperatures and the T_g is below -40°C. The hydrolytic stability data does show some changes in material properties, the extent of which may be clouded by the test accuracy.

3.8 Transfer Molded Thermoset Compounds

Transfer molded thermosets are also used to manufacture electronic components, but not to encapsulate electronic circuitry. The primary reasons are the higher temperatures and pressures associated with the processes, as well as the inherently low work-to-break properties associated with many thermoset compounds.

Based on the discussion and survey conducted in Section 2.2, a thermoset requiring relatively low molding temperature and pressure was selected for testing. Samples of Hysol Hiflow MG5F were compression-molded into test specimens and tests conducted.

3.8.1 Demold and Cure Evaluation

A variety of cure conditions was evaluated to determine the minimum cure temperature and pressure required to achieve stable ½ x ½ x 6-in. test specimens. A transfer pressure of 50 psi and a cure cycle of 15 minutes at 107°C were found to result in acceptable specimens. Heat can be increased to produce a 1- to 2-minute cycle at 150°C. The 107°C temperature was used to prepare these test specimens.

3.8.2 Flexural Properties

Flexural strength, modulus and work to break properties were measured by three-point loading per ASTM-D-790 using a four-inch span and a crosshead speed of 0.05 in. per minute. Table XXX shows the material to have a low work-to-break point, indicating a high brittleness when compared to the filled epoxies in Section 3.4.2. The flexural properties measured on these compression-molded samples are lower than those expected of transfer molded samples.

TABLE XXX: FLEXURAL PROPERTIES OF MOLDED THERMOSET MATERIAL (HYSOL MG5F)

Property	Value
Density	1.90
Flexural strength, psi	5100
Flexural modulus, psi	0.76×10^6
Work-to-break, in.-lb/in.^{2}	5.7

3.8.3 Thermal Expansion (CTE) and Glass Transition Temperature (T_g)

The CTE and T_g were measured on cured specimens using a Perkin-Elmer TMA at a scan rate of 10°C per minute. The values measured (Table XXXI) show the T_g above the 71°C requirement and the CTE comparable to filled epoxy systems.

TABLE XXXI. THERMAL PROPERTIES OF MOLDED THERMOSET MATERIAL (HYSOL MG5F)

Property	Value
CTE, in./in./°C	40×10^{-6}
T_g, °C	+93

3.8.4 Hydrolytic Stability

Specimens were cut from cured bars of material and subjected to the environment required per MIL-I-16923G. Tests were made to determine the Barcol 934-1 hardness periodically through the 120-day test cycle. Table XXXII

shows virtually no change in hardness in this test. Figure 11 shows a graph of the data.

TABLE XXXII. HYDROLYTIC STABILITY OF MOLDED THERMOSET MATERIALS

	Barcol 934-1, Hardness of Specimens:	
Aging Time	Aged at 71°C + 90% RH	Aged at 23°C + 50% RH
0 days	45	45
28 days	45	43
56 days	43	47
84 days	44	44
120 days	44	45
Total change, %	-2.2	0

3.8.5 Summary

The properties measured on the Hysol Hiflow MG5F thermoset indicate that the lower cure-temperature and pressures are close to those currently used in cast materials, with a significant reduction in cure time. Due to the equipment required for transfer or compression molding, it may be desirable to reduce the cure cycle by increasing the cure temperature to achieve additional economies.

The mechanical and thermal properties of this material compare favorably with cast epoxy materials, with the exception of a low work-to-break point.

3.9 Material Selection to 10 Candidates

At the conclusion of the material testing phase of this program, 10 materials were chosen for further evaluations with test electronic circuits. The selections were based on the materials' test results as well as on the improvement in demold times for commonly used encapsulants. The selection of these materials does not necessarily imply that these candidates are the best in the industry for electronic encapsulation, but rather is the result of the various trade-offs described above and the time limitation of the program.

Table XXXIII lists the materials chosen from the test program to be evaluated as an encapsulant for electronic circuits. The materials selected represent most of the material categories from the previous phase, and include one standard, Isofoam PE-18 foam, for which previous data had also been obtained. The infrared spectra of these 10 candidates are found in Appendix D.

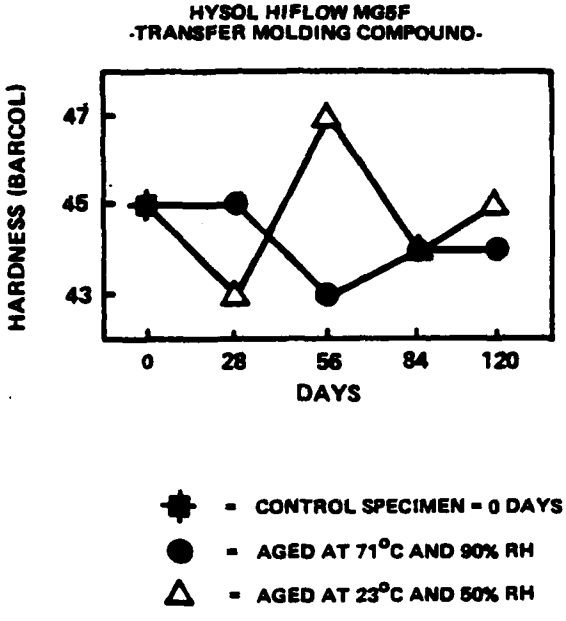

Figure 11. Thermoset material hydrolytic stability.

TABLE XXXIII. TEN CANDIDATE MATERIALS

Code	Material	Vendor	Type
1	Coro-foam 589	Cook	Chemically blown MDI urethane foam
2	Isofoam PE-18	Witco	Chemically blown TDI urethane
3	PR2036	Formulated Resins	Two-component syntactic foam
4	Scotchcast XR5090	3M	Two-component syntactic foam
5	NB509-70-2	Hysol	One-component syntactic foam
6	Stycast 1495/ Catalyst 9	Emerson & Cuming	Two-component filled epoxy
7	E0-0029	Hysol	One-component filled epoxy
8	Hiflow MG5F	Hysol	Transfer molded epoxy
9	ISP-100	Dow	Two-component urethane (>70D)
10	B635/1-4BD	Uniroyal	Two-component urethane (<70D)

4. CIRCUIT ENCAPSULATION

4.1 Introduction

This phase of the program evaluated the behavior of the candidate materials as encapsulants for electronic circuitry typical of that used by HDL for artillery and mortar fuzing. By encapsulating actual circuits, refinements could be made in processing and fill characterization, and in the demold and full cure determinations. The effect of these materials on the circuitry could also be evaluated.

Two circuit boards were used in this evaluation. The first was a thick-film hybrid circuit used in the M734 mortar fuze. The total circuit performance was measured. The second was a discrete component glass-epoxy circuit board containing historically sensitive components each of which could be tested individually.

Encapsulated circuits were returned to HDL for electrical, mechanical, and environmental testing. An initial group involved five samples of each circuit type using the 10 encapsulant candidates. A second group of 10 samples of five encapsulants was also prepared and then tested by HDL. The selection of this second group was based upon observations during fabrication of the first group of encapsulated circuits.

4.2 Circuit Types

4.2.1 Thick-Film Hybrid Circuit

The M734 mortar fuze amplifier circuit is a typical thick-film hybrid ceramic circuit. This circuit (Figure 12) is a standard printed-and-fired thick film with various attached discrete components including tantalum and ceramic capacitors, and precoated chip-and-wire active components. The 0.025-in. thick ceramic substrate is 1.417 in. in diameter with a 0.535-in. diameter center hole. The pinout for the circuit is along one side, with solder pads for attachment. The total circuit performance is the best measurable output of the circuit. The effect of encapsulation on individual components cannot be readily determined.

This circuit was used to evaluate the flowability of the encapsulants and effect of encapsulation on components and, specifically, the brittle ceramic substrate.

Figure 12. M734 amplifier thick-film hybrid circuit.

4.2.2 Glass-Epoxy (G-10) Printed Circuit Board

A circuit was specifically designed and fabricated by HDL on which the effect of encapsulants on individual components could be evaluated. Components were selected from those which prior experience had shown are most sensitive to encapsulation.

Several fragile components, such as glass diodes, small resistors, and chokes, were included as characteristic of components which are sensitive to embedment and thermal expansion stresses. A molded capacitor with sharp corners was included as a crack generator. Fragile components were positioned near the corners of this capacitor. A liquid tantalum capacitor was used as a heat-sensitive component. Finally, a nonfunctional 14-pin DIP was placed on the board as a flow restrictor to evaluate the fill characteristics of the materials. Figure 13 shows the circuit layout. The board diameter and readout locations were the same as the M734 amplifier, permitting use of the same tooling for encapsulation.

4.3 Encapsulation Technique

4.3.1 Liquid Encapsulants

Five single-cavity aluminum molds were fabricated for the liquid encapsulants. The circuits were supported on the center diameter (Figure 14) in four locations in such a way to allow an equal volume of encapsulant on both sides of the board. Components and edges of the boards were covered by at least 1/16-in. of encapsulant.

Lead wires were soldered to the terminals with 1/16-in. wire. Rubber pads were used to mask these leads in the mold. The mold was gated at 90° from the leads and a material well used for gravity feed. A knockout system was used to remove the part from the cavity.

The candidate encapsulants and molds were preheated as appropriate. The encapsulants were then mixed and poured into the cavities. Following the appropriate heating cycle, the parts were removed, deflashed, and inspected. Conformal coatings were not used on the circuits.

4.3.2 Transfer Molding Technique

A single-cavity transfer mold was fabricated using the same circuit centering design and gating technique as discussed in Section 4.3.1. Several trials were made to determine the optimum preform, preheat temperature, mold temperature and pressure, and cure time. A cycle of 15 minutes at 225°F was used with low-temperature preheated preforms. A 50-psi transfer pressure was found adequate to fill the mold. A 0.005-in. conformal coating of MIL-A-46146

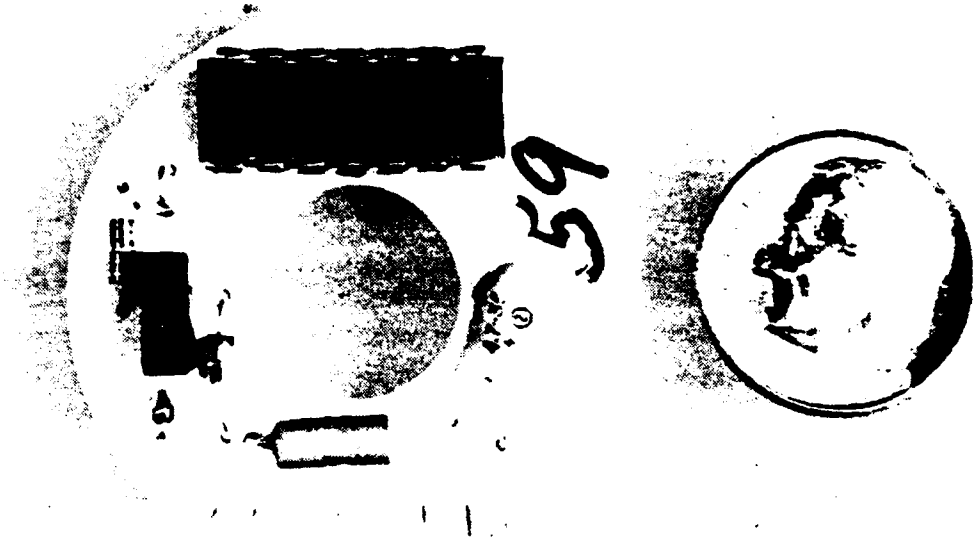

Figure 13. Discrete component circuit.

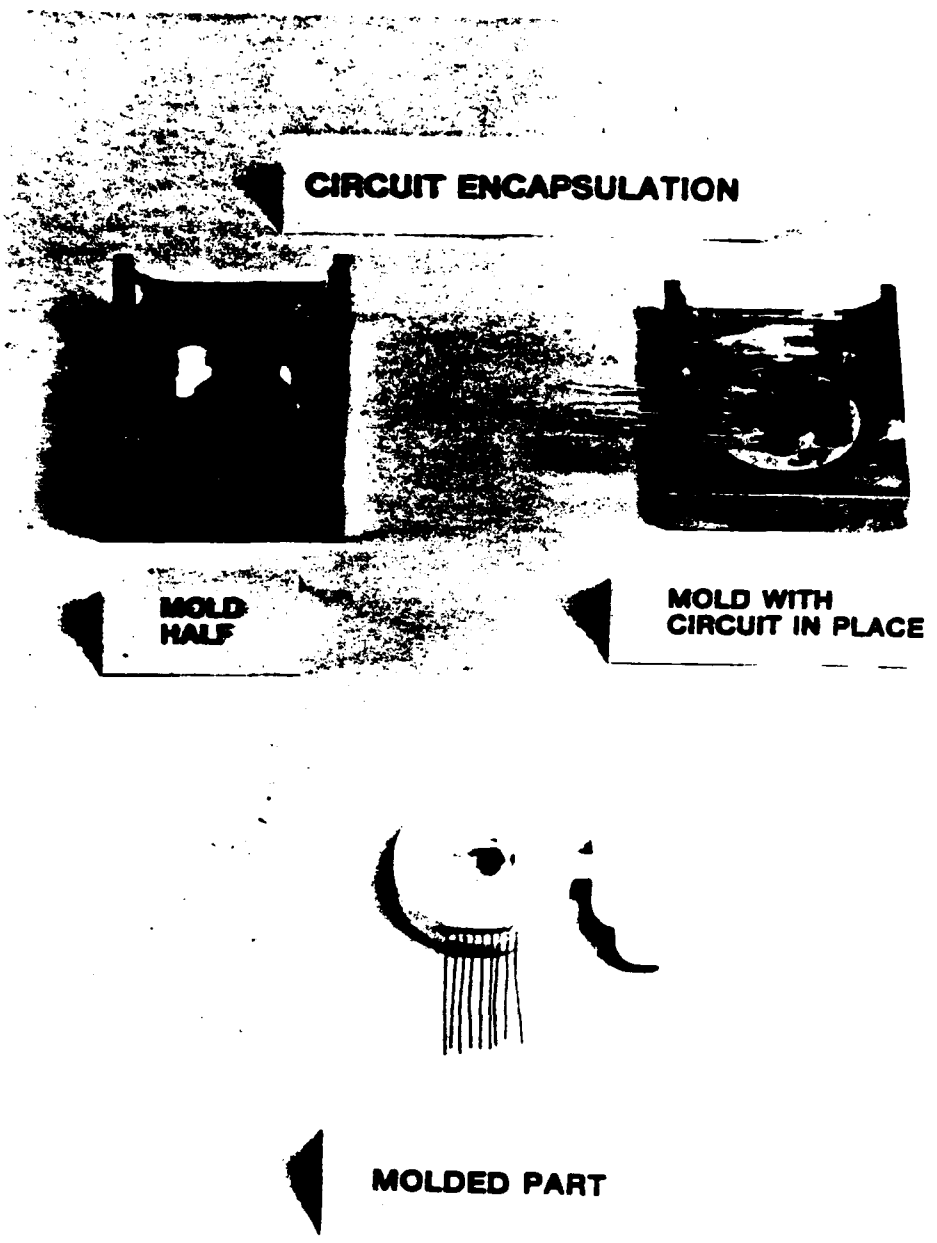

Figure 14. Mold for a circuit encapsulation with liquids.

silicone was used to reduce internal stresses on the electronics after molding. The same procedure was used with both types of circuits.

4.4 Circuit Testing

All circuits were tested by HDL for pre- and post-encapsulation electrical performance. A go/no-go test was provided to Honeywell for the evaluations on the hybrid circuits. This procedure involved applying 25 V of current to pads AC-1 and AC-2 in a forward and reverse direction. The cyclic testing of a single unit yielded a standard deviation of 0.06-mA current drain. This technique was used by Honeywell before and after encapsulation to assist in the process development for each candidate. All tests on the discrete circuits were performed by HDL. The results of HDL testing, including environmental and shock tests, will be reported separately.

4.5 Results

Each of the 10 candidate materials was evaluated for their ease of handling, demold times, and effect on electrical performance. Process variables were adjusted for the decrease in volume of material required to encapsulate the circuits as compared to the volume used in preparing test specimens. (Table XXXIV summarizes the results obtained.) Five hybrid and five glass-epoxy boards were encapsulated with each candidate.

4.5.1 Cook Coro-foam 589 Urethane Foam

The Cook Coro-foam 589 samples were prepared at 23°C by hand mixing a 100-gram batch. All five molds were filled from the same batch. A 30-sec mixing time was used, with an additional two minutes available for working time. The material was placed into syringes and then transferred into the cavity. A plug was inserted into the transfer port for 15 sec to provide backpressure to the rising foam. Molding trials showed that a one-hour demold time at 23°C was required to allow the parts to be removed from the mold without damage. The parts were subsequently cured for 7 days at 23°C prior to electrical tests.

The electrical tests revealed that no significant changes were found due to encapsulation. Changes of -0.02 to +0.08 mA were measured.

4.5.2 Witco Isofoam PE-18 Urethane Foam

The Witco Isofoam PE-18 samples were prepared by hand mixing a 100-gram batch with the components at 23°C. The same batch was used to fill all five molds. After a 30-sec mixing time, an additional two minutes of working time was available. The material was placed into syringes and then transferred into the cavity. A 10-sec backpressure was applied to aid in mold filling. The process trials demonstrated that a one-hour demold time at 65°C allowed the part to be removed without damage. Trials at 23°C yielded material that

TABLE XXXIV. ENCAPSULATION RESULTS

Product	Type	Initial Cure Demold	Post-Cure	Handling	Go/No-Go Electrical Test Results On Hybrids	Remarks
1. Cook Coro-foam 589	Chemically blown foam	1 hr @ 23°C	7 days @ 23°C	Good - mix 30 sec, 2 additional min to pour. Apply 15 sec backpressure.	Pass	Best foam - 1:1 ratio; low viscosity.
2. Witco Isofoam PE-18	Chemically blown foam	1 hr @ 65°C	7 days @23°C	Good - mix 30 sec, 2 additional min to pour. Molds at 65°C. Apply 10 sec backpressure.	Pass	Close to material 1; oven cure necessary; higher viscosity,
3. Formulated Resins PR2036	Syntactic foam, two compponent	1-1/2 hr @ 65°C	7 days @ 23°C	Excellent - molds at 65°C. Return parts to R.T. before demolding. Some settling.	Pass	Best syntactic system.
4. 3M Co. Scotchcast XR5090	Syntactic foam, two component	2 hr @ 65°C	7 days @ 23°C	Fair to good - quite thixotropic, warm material to 65°C. Return molds to R.T. to demold. Some settling.	1 of 5 failed	Material must be kept at 150°F for good handling; rapid heat loss causes thixotropic condition.
5. Hysol NB509-70-2	Syntactic foam, one component	No gel after 3 hr @ 74°C	13 hr @ 74°C	Good, molds at 74°C, excessive settling of resin (glass filler floats).	Not tested	Extremely long gel time -- 4 hrs. Overnight cure necessary; excessive settling of resin (runs out of mold during cure). Surface inhibition of resin (resin will not postcure). Stopped casting units after ruining hybrid substrates.
6. Emerson and Cuming Stycast 1495/ Catalyst 9	Castable epoxy, two component	1 hr @ 65°C	7 days @ 23°C	Very good - molds at 65°C, pour and cure direct at 65°C.	Pass	Best castable epoxy system.
7. Hysol EO-0029	Castable epoxy, one component	3 hr @ 74°C	13 hr @ 74°C	Fair to good, quite thixotropic, material and molds at 74°C.	Pass	Long demold time at 74°C, high thermal shrinkage away from surface.
8. Hysol Hiflow MG5F	Transfer molding compound	15 min @ 107°C		Fair to good - due to high CTE, must use conformal coating on ceramic substrate and glass diodes.	3 of 3 failed	High CTE problems on ceramic substrates requiring conformal coating; hard to get proper flow in mold.

TABLE XXXIV. ENCAPSULATION RESULTS (CONT'D)

	Product	Type	Initial Cure Demold	Post-Cure	Handling	Go/No-Go Electrical Test Results On Hybrids	Remarks
9.	Dow ISP-100	Castable urethane two component (> 700)	1 hr @ 65°C	7 days @ 23°C	Good, very fast system, 2 drops stannous octoate per 37 gm batch, mix 15 sec, 15 sec to pour. Parts are brittle and cannot be demolded at R.T. cure; run R.T. mold and R.T. material with 150°F cure. Exotherm does not exceed oven temperature when material is poured in R.T. mold. Exotherm in a tin dish at R.T. is 82°F in 2-1/2 min. (37 gm batch), no evacuation.	Pass	Best urethane; only bad points are fast pot life and being a 3 component system.
10.	Uniroyal 8635/1-480	Castable urethane two component (< 700)	30 min. @ 82°C	7 days @ 23°C	Good, fast system. Must use catalyst, one drop dibutyl tin dilaurate per 100 gm resin. No time to evacuate, R.T. material, molds at 82°C.	2 of 5 failed	Material too fast to evacuate; excessive trapped air; 3 component system.

was very friable and crumbled during demolding. The parts were cured for 7 days at 23°C prior to electrical tests. The test results show changes ranging from -0.27 to +0.10 mA due to encapsulation. While this is more change than noted with the Cook foam, the values are acceptable.

4.5.3 Formulated Resins PR 2036 Two-Component Syntactic Foam

These samples were prepared by preheating the components and the molds to +65°C, then hand-mixing the system and filling the cavity by gravity feed. A demold time of 1.5 hours at 65°C was required to remove the part without damage. Minor floating of the glass bead filler was noted. After 7 days at 23°C, the electrical test results showed changes ranging from from -0.18 to +0.13 mA, which are acceptable.

4.5.4 3M Scotchcast XR5090 Two-Component Syntactic Foam

The samples were prepared by preheating the components and the molds to +65°C, then by hand-mixing the system and filling the mold cavity by gravity feed. The material was nearly thixotropic when introduced into unheated molds. This resulted in an incomplete fill. A demold time of 2 hours at 65°C was achieved. Following a 7-day cure at a 23°C, the electrical test results showed one circuit had changed -1.03 mA. This was considered a failure. The remaining circuits had changed -0.07 to +02 mA.

4.5.5 Hysol NB509-70-2 Single-Component Syntactic Foam

Difficulty was encountered with the vendor's second batch of this single-component syntactic foam. The resin would not cure properly at 74°C, and would not respond to a postcure of 13 hours at 74°C. Conversations with the vendor confirmed the existence of problems with the cure system. All testing was stopped.

4.5.6 Emerson and Cuming Stycast 1495/Catalyst 9 Filled Epoxy

This filled epoxy exhibited very good handling properties when preheated to 65°C and cast into preheated molds. A demold time of one hour at 65°C was achieved. Parts were cured for 7 days at 23°C. Electrical tests showed changes ranging from -0.11 to +0.39 mA, which were considered acceptable.

4.5.7 Hysol E-0029 Single-Component Filled Epoxy

This material had fair to good handling properties when heated to 74°C and cast into preheated molds. The viscosity of the material was high, making a complete fill of the cavity somewhat difficult but not impossible. A three-hour demold time at 74°C was achieved. An additional 13 hours at 74°C outside the mold was required for a full cure. Upon being demolded, some shrinkage of the

material was noted. The electrical tests showed changes ranging from -0.01 to +0.20 mA.

4.5.8 Hysol Hiflow MG5F Transfer Molding Epoxy

Conformal coatings were used on the entire ceramic circuit boards to prevent cracking of the encapsulant immediately after molding. Filling was accomplished by transfer molding into a single cavity mold. A demold cycle of 15 minutes at 107°C was achieved using a 50-psi transfer pressure. There was difficulty in obtaining complete cavity fills on both the ceramic and glass epoxy boards. Electrical tests showed that three of three ceramic boards failed, losing all electrical continuity. Five glass epoxy boards were molded with conformal coating on the glass diodes.

4.5.9 Dow ISP-100 Semirigid Urethane

The samples of Dow ISP-100 were prepared individually in 37-gram batches, catalyzed with two drops of stannous octoate. The low viscosity of the system resulted in no air entrapment and easy fill of the cavity. The rapid reaction rate at 23°C allowed a maximum of 15 sec for mixing, and 15 sec for pouring and fill. Trials at 23°C produced a brittle encapsulant that was damaged during demolding. When the resin was poured into 23°C molds and cured at 65°C, a 1-hour demold time was achieved. Despite an 82°C exotherm observed in a 37-gram batch within 2.5 minutes when the resin was cured in an aluminum dish, no exotherm was measured in molded samples. The mold acted as a heat sink during this period. Electrical tests conducted after 7 days at 23°C found changes ranging from +0.05 to +0.40 mA.

4.5.10 Uniroyal B635/1,4-BD Flexible Urethane

One drop of dibutyltin dilaurate was required to achieve a demold time of 30 minutes at 82°C. The material was hand mixed for 15 sec and poured into an 82°C mold. With the resin components at 23°C, a very rapid reaction time did not allow for deaeration. No fill problems were experienced, although air was entrapped. Electrical tests showed two of five circuits lost continuity, probably due to broken ceramic substrates. The remaining circuits showed changes ranging from -0.01 to +0.07 mA.

4.6 Selection of Five Materials

Based on the observations made during the initial encapsulation phase and initial electrical tests at HDL, five materials were selected for fabrication of additional test samples. Five circuits of both hybrid and glass-epoxy boards were prepared using the same procedures as in Section 4.5. The candidates chosen were

A. Cook Coro-foam 589
B. Emerson and Cuming Stycast 1495/Catalyst 9
C. Dow ISP-100
D. Hysol E0-0029
E. Formulated Resins PR2036

Following encapsulation, the electrical go/no-go test was performed on the hybrid circuits at Honeywell. The results showed only minor changes, except for one high-value circuit with Stycast 1495 and one failed (low) circuit with Hysol E0-0029.

The encapsulated circuits were sent to HDL for further electrical tests before and after environmental and shock tests. The results of these tests will be reported separately.

5. COST ANALYSIS

5.1 Introduction

The choice of an encapsulant for ordnance electronics encompasses many tradeoffs. These include functional requirements, state-of-the-art knowledge in materials, prior experience with encapsulants, and costs. The various material types discussed in this program possess a large number of variables which affect the eventual cost of encapsulation. For example, a single component material requires less complex equipment and eliminates several inspection tests, but has a longer cure time, special storage conditions, and generally higher cost. Two component systems require virtually the opposite. Chemically blown foams are processed differently than syntactic foams as well as silica-filled epoxies, urethanes, and other elastomers. Compression, transfer, or injection molding have significantly different processing and tooling requirements.

Assuming that equivalent function can be achieved, the choices of the encapsulant and production process for electronic encapsulation vary significantly in cost and complexity. Understanding the factors associated with these materials and their respective processes is critical to achieving a cost-effective production process. In addition, once an encapsulant type has been selected, there are alternative cure times, cure temperatures, mold types, number of components, or conformal coating requirements.

The eight material types evaluated in this program were compared to quantify the nonrecurring and recurring costs associated with their use, and to identify the cost drivers. By quantifying these factors, the major cost items can be identified and cost-saving approaches presented.

5.2 Assumptions

To obtain the relative cost of producing encapsulated electronics in high volume, several assumptions have been made.

5.2.1 Production Volume

A production rate of 100,000 units per month for one year is the basis of comparison. This is sufficient volume to allow the liberal adaptation of moderate to high-volume concepts. As such, no consideration has been given to hand or manual operations. A production rate of 100,000 parts per month equates to 5,000 units per day or 4.75 sec per unit on a single shift of 8 hours for a 5-day week (1-8-5). The work year contains 240 days.

5.2.2 Production Facility

It is assumed that the facility is in complete operation. The cost of setting up and debugging the facility is not included. Major equipment and facility costs are separately identified for each material category. Floor space is estimated at $1 per square foot per month.

5.2.3 Labor Rates

A labor rate of $25 per hour is used for factory labor costs. All engineering support and quality departments are rated at $35 per hour. An 82% efficiency factor is used. Labor operations which are identical in all material categories are not costed, as this does not affect the relationship of one system to another. Examples of this are the labor to transfer the electronics from one department to another, the labor to produce the electronics, and the labor to package, test, or ship the final unit.

5.2.4 Material Volume

The M734 fuze amplifier circuit was the model for this comparison. A material volume of 17 cm^3 per part was used. The necessary weight of each material was then calculated from specific gravities. Material losses due to handling and scrap are consistent with those expected with each encapsulant type. Table XXXV shows the quantity needed and cost of each material based on volume discounts.

5.2.5 Material Categories

Eight material categories were evaluated. These represented the 10 materials studied in Section 4. In addition, a silica-filled epoxy requiring a 16-hour cure at 65°C has been included as a standard, since there is a great deal of production experience with it available at Honeywell. The demold and cure requirements determined in Section 4 have been used in generating the costs for this comparison.

The individual material categories in this study are as follows:

1.0 Two-Component Filled Epoxy
- 1.1 MH20245 Standard
- 1.2 Emerson and Cuming Stycast 1495/Catalyst 9

2.0 One-Component Filled Epoxy
- 2.1 Hysol E0-0029

3.0 Two-Component Syntactic Foam
- 3.1 Formulated Resins PR2036
- 3.2 3M XR5090

TABLE XXXV. MATERIAL COSTS

Material		Specific Gravity	Pounds Per 1000 Units[b]	Handling Loss (%)[c]	Total Lb Per 1000 Units	Pounds Per Year	Cost Per Pound	Cost Per 1000 Units	Cost Per Year
Type 1.	Two-component filled epoxy								
1.1	MH20245P (Hysol)[a]	2.05	80.0	4.5	83.6	100,320	$ 1.35	$112.86	$135,432
1.2	Emerson & Cumming Stycast 1495/Catalyst 9	1.87	73.0	4.5	76.3	91,560	$ 1.30	$ 99.19	$119,028
Type 2.	One-component filled epoxy								
2.1	Hysol EO-0029	1.73	67.4	1.8	68.6	82,320	$ 1.90	$130.34	$156,408
Type 3.	Two-component syntactic foam								
3.1	Formulated resins PR 2036	0.86	33.2	4.5	34.7	41,640	$ 2.50	$ 86.75	$104,100
3.2	3M XR 5090	0.87	34.0	4.5	35.5	42,600	$11.58	$411.09	$493,308
Type 4.	One-component syntactic foam								
4.1	Hysol NB509-70-2	0.85	33.2	1.8	33.8	40,560	$ 6.30	$212.94	$255,528
Type 5.	Chemically blown foam								
5.1	Cook Coro-foam 589	0.26	10.14	15.0	11.7	14,040	$ 1.03	$ 12.05	$ 14,461
5.2	Witco Isofoam PE-18	0.25	9.76	15.0	11.2	13,440	$ 1.46	$ 16.35	$ 19,622
Type 6.	Semi-rigid urethane (70D)								
6.1	Dow ISP-100	1.13	44.0	7.5	47.3	56,760	$ 0.92	$ 43.52	$ 52,219
Type 7.	Flexible urethane (70D)								
7.1	Uniroyal B635/1,4 BD	1.15	44.8	7.5	48.2	57,840	$ 1.91	$ 92.06	$110,474
Type 8.	Transfer molding powders procured in sized preformed state								
8.1	Hysol MG5F	1.9	74.2	0.5	74.6	89,520	$ 2.91	$217.09	$260,503

[a] Honeywell proprietary product custom compounded by Hysol Corp. and/or Epic Resins. Hysol Corp. costs are used herein. This product is used by Honeywell Inc. Defense Systems Division for up to 20 years in approximately 20 separate electronic devices encapsulated specifically for military field use.

[b] Includes material loss from receipt of material to use on the production line.

[c] Represents the loss on the production line due to handling, purging, etc.

4.0 One-Component Syntactic Foam
  4.1 Hysol NB509-70-2
5.0 Chemically Blown Foam
  5.1 Cook Coro-foam 589
  5.2 Witco Isofoam PE-18
6.0 Semi-rigid Urethane (70D)
  6.1 Dow ISP-100
7.0 Elastomers (70D)
  7.1 Uniroyal B635/1,4BD
8.0 Transfer Molding Compound
  8.1 Hysol MG5F

5.3 Material Comparisons

The recurring and nonrecurring costs for each material type discussed in Section 5.2.5 are compared in Figure 15. The materials are listed in the order of increasing recurring costs. The use of integral molds is assumed for all liquid encapsulants, while the use of permanent (nonrecurring) tooling is assumed for transfer molded material. The costs of conformal coating is included for filled epoxy, semirigid urethane and the transfer molding compound.

A review of this chart shows that in general, chemically blown foams are the least costly materials while filled epoxy systems are the most. The nonrecurring costs track the recurring costs except for the transfer molding compound, where a large equipment outlay is required. In this case, the nonrecurring costs can be greatly reduced by the use of shorter cure cycles, as will be discussed in Section 5.9.

Figure 16 breaks down the recurring costs into labor, material, temporary tooling, floor space, and energy. There is a large difference in the labor and material costs for each material. The floor space and energy costs are minor factors in the overall costs.

The detailed cost breakdown of each material type is found in Appendix C.

5.4 Mold Concept Comparisons

Three mold concepts were evaluated for high-volume production. The first was matched metal molds in which a replaceable aluminum die-cast cavity is employed. A useful life of 500 cycles is assumed. The second concept uses the same metal clamping fixtures, but with plastic inserts having useful lives of 150 cycles. The plastic insert eliminates the need for an application of mold release. The third concept was an integral potting cup that would be attached with centering features to the electronics and would remain a part of the completed electronic part.

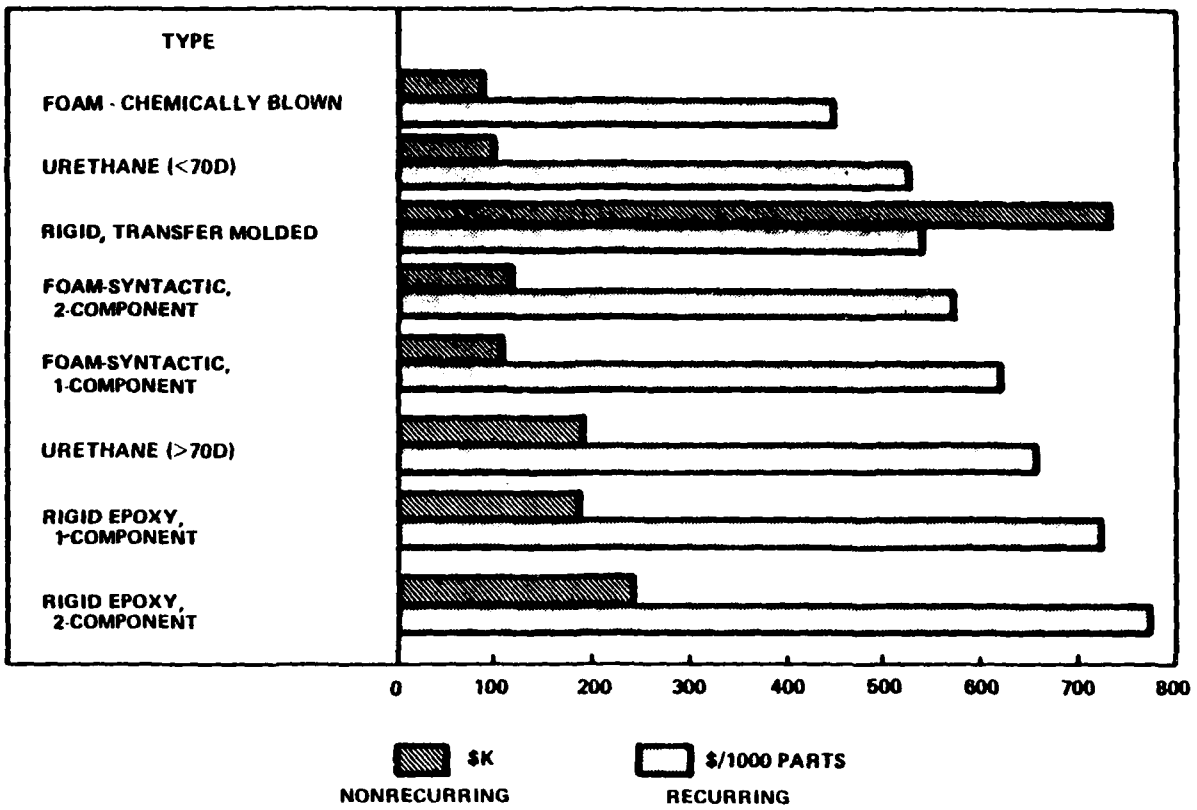

Figure 15. Comparison of recurring and nonrecurring costs.

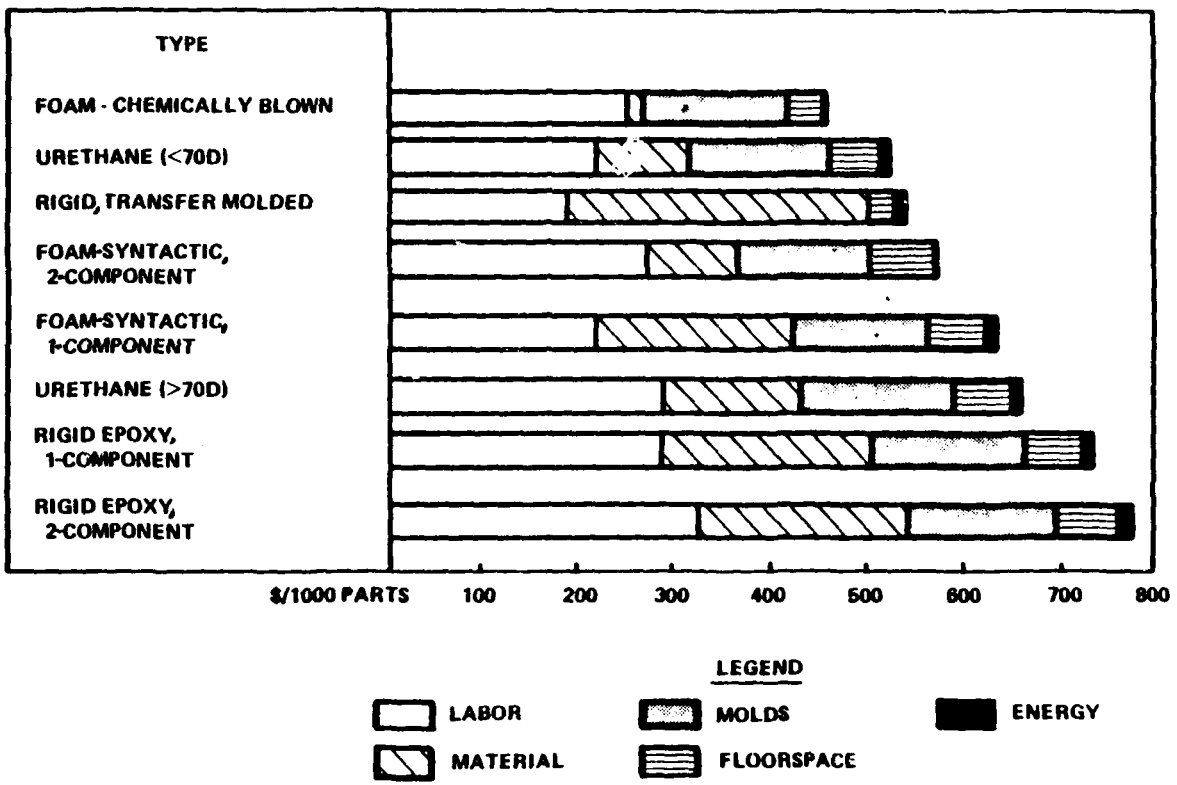

Figure 16. Breakdown of recurring costs.

Appendix A is a review of the mold and labor costs for each concept. While the cost for integral molds is higher than for the versions with inserts, the labor associated with this concept is considerably less. Table XXXVI shows that there is as much as 58 percent cost saving with integral molds when compared to the molds with metal inserts. The use of plastic inserts instead of the aluminum inserts can save up to 34 percent of the tooling costs. The major cost items include the labor for applying the mold release, assembling the mold, demolding, and mold cleaning.

TABLE XXXVI. EFFECT OF TOOLING CONCEPTS (1-HOUR DEMOLD)

Parameter	Matched Metal, Die-Cast Insert	Matched Metal Plastic Inserts	Integral
Life expectancy, cycles	500	150	1
Mold cost per 1000 parts (per year)	$ 69 ($82.8K)	$ 91 ($109.2K)	$152 ($182.4K)
Labor cost per 1000 parts (per year)	$390 ($468K)	$215 ($258K)	$ 40 ($48K)
Total cost per year	$550.8K	$367.2K	$230.4K
Potential Savings	—	$183.6K (33%)	$320.4K (58%)
	Major Cost Items • labor - mold release application - assembly - demolding - cleaning		

5.5 Conformal Coating

Two techniques of conformal coating were evaluated. The first involves the application of a 3- to 5-mil thick silicone coating on approximately three selected components using a rotary application machine. The second is a dip coating of the same material over the entire circuit board using a conveyorized dip and drying machine with heat and humidity areas to cure the coating. Appendix B details the equipment and labor costs associated with these processes.

Using a rigid, filled epoxy the cost of conformal coating the entire board is $239K per year (Table XXXVII). Elimination of the need for a conformal coating would thus save about 22%.

TABLE XXXVII. EFFECT OF CONFORMAL COATING WITH TWO-COMPONENT RIGID, FILLED EPOXY

Material	Nonrecurring Costs	Recurring Costs	Total Cost per Year	Potential Saving
Coated	$206K	$768/M	$1073K	$239K (22%)
Uncoated	$130K	$587/M	$ 834K	
		Major Cost Items		
	Item	Cost Difference	Cost Difference Per Year	
	Equipment	$ 76K	$ 76K	
	Material	$113K	$113K	
	Labor	$ 17/M	$ 20.4K	
			$209.4K	

5.6 Effect of Cure Time

The cost difference between a material that cures in one hour at 65°C versus one of the same material type that cures in 16 hours at 65°C can also be calculated. Table XXXVIII shows this comparison for rigid, filled epoxies. With the use of integral molds, up to a 7-percent savings can be achieved with the material requiring the shorter cure time. These savings are reflected primarily in the costs of ovens, energy, and floor space required to support the longer cure time.

TABLE XXXVIII. EFFECT OF CURE TIME (RIGID EPOXY)

Material	Nonrecurring	Recurring	Total Cost Per Year	Potential Saving
65°C preheat; 1 hour @ 65°C demold	$206K	$723/M	$1,073K	$94K (8%)
65° preheat; 16 hour @ 65°C demold	$245K	$768/M	$1,167K	
	Major Cost Items			
	Item	Cost Difference	Cost Difference Per Year	
	Oven	$35K	$35K	
	Energy	$ 5/M	$ 6K	
	Floor space	2700 Ft^2	$32.4K	
			$73.4K	

5.7 Effect of Number of Components

The advantage of a single component versus two-component material using the same cure cycle can be seen in Table XXXIX. A 9.3% cost saving is possible, primarily due to lower equipment, floor space, and labor costs. This saving is possible even though the material and storage costs are higher.

TABLE XXXIX. *EFFECT OF NUMBER OF COMPONENTS (RIGID EPOXY)*

Material	Nonrecurring	Recurring	Total Cost Per Year	Potential Saving
One component 16 hour @ 65°C demold	$188K	$724/M	$1,057K	
				$110K (9.4%)
2 components 16 hour @ 65°C demold	$245K	$768/M	$1,167K	

Major Cost Items

Item	Cost Difference	Cost Difference Per Year
Material	$17.5/M	$ 21K
Dispenser	$56.6K	$ 56.6K
Floor space	1200 ft^2	$ 14.4K
Labor	$48/M	$ 57.6K
		$107.6K

5.8 Effect of Cure Temperature

An 18% cost reduction is possible if cure can be attained at room rather than elevated temperature. Table XL shows this comparison for chemically blown urethane foams. The saving is due to the need for less equipment, labor, energy, and floor space.

TABLE XL. EFFECT OF PROCESSING TEMPERATURE (CHEMICALLY BLOWN FOAMS)

Material	Nonrecurring	Recurring	Total Cost Per Year	Potential Saving
Room temperature; 1 hour demold	$45K	$457/M	$593K	
				132K (18%)
65°C preheat; 1 hour at 65°C demold	$83K	$532/M	$725K	
		Major Cost Items		
	Item	Cost Difference	Cost Difference Per Year	
	Oven	$35K	$ 35K	
	Energy	$ 3.5/M	$ 4.2K	
	Labor	$60/M	$ 72K	
	Floor space	1200 ft^2	$ 14.4K	
			$125.6K	

5.9 Liquid Versus Transfer Molding

Transfer molding materials and their associated presses are not profitable on a 1-year basis if the relatively long cure time of 15 minutes is used, because of the large nonrecurring costs. The recurring costs, however, are low enough to suggest that a significant savings can be obtained on a longer production run. Table XLI allows us to compare a liquid-filled epoxy system with a transfer molded epoxy. A second comparison can be made for two different cure cycles of the transfer molding material. Increasing the cure temperature can significantly reduce the equipment requirements and result in a potential 42% savings.

TABLE XLI. LIQUID VERSUS TRANSFER MOLDED

Material	Nonrecurring	Recurring	Total Cost Per Year	Potential Saving
Transfer molded, rigid; 15 minutes @ 107°C demold	$724K	$434/M	$1245K	
				-$172K (-16%)
2-component, rigid; 1 hour @ 65°C demold	$207K	$723/M	$1073K	
				$448K (42%)
Transfer molded, rigid; 1 minute @ 150°C demold	$171K	$378/M	$625K	
		Major Cost Items		
		Facilities Labor Floorspace		

5.10 Cost Drivers

A review of the costs shows that the material type is a main factor in determining the cost of encapsulation. Furthermore, from the examples cited, several alternative material characteristics can also greatly affect the cost (see Table XLII). If several of these options are used together, the savings can be cumulative. For example, a room-temperature cure with a one-hour demold time that does not require a conformal coating could save up to 44 percent of the cost of encapsulation when compared to that of a liquid rigid epoxy system. In addition, if an integral molding concept is used, the total savings could reach 70%. The probability of combining all of these cost-reduction features is low. This exercise is simply meant to bring these areas to light for consideration in choosing a material and production technique.

TABLE XLII. MAJOR COST DRIVERS

Cost Drivers	Potential Saving	Percentage of Liquid Rigid System's Cost
• Cure time	$ 93K	8%
• Number of components	$109K	9%
• Processing temperature	$134K	11%
• Conformal coating	$281K	22%
• Tooling concepts	$184-320K	15%-26%
• Transfer molding	$534K	42%

6. SUMMARY AND CONCLUSIONS

This program to evaluate encapsulating plastics for ordnance electronic assemblies resulted in the narrowing of the broad field of plastics to five materials. These materials have passed rigorous military tests and represent several categories of material which can immediately be considered for current application.

These materials were selected to minimize the demold time of typical encapsulants currently in standard usage. The cost analysis performed points out that several of these materials result in significant cost savings, not only from a reduced cure time, but also from lower processing temperatures. The single-component material identified also realizes cost savings over two-component material by reducing the complexity of material handling.

While this program was limited in scope, the areas of thermoplastic and thermoset molding materials appear to offer another avenue of cost advantages in electronic encapsulation. While there are many unknowns in the behavior of electronic circuits in these molding environments, the simple features of these techniques are attractive and cost effective.

Attention to tooling concepts in the early circuit and device design can take advantage of approaches to enable the use of integral molds, thus eliminating the large recurring costs of building and using molds.

APPENDIX A
MOLD COST COMPARISONS: TOOLING FOR MOLDS

I. MOLD CONCEPTS

Concept A, Matched Metal Molds:
(Assumes 500 cycles per mold)

		Nonrecurring	Recurring
1.	Make aluminum die-cast mold of 2 upper and 2 lower cavities per operation.	$ 45,000.00	
2.	Make rubber mold for rubber seal off strips for leadwires.	2,800.00	
3.	Make rule die-cutter for rubber pads including air press.	8,000.00	
4.	Make clamping fixtures to gang 7 mold sets together. 260 hr/M		$ 6,500.00/M
5.	Die-cast molds, 2 cycles/min = 4 molds/min = 4.5 hr/M		112.50/M
6.	Mold and cut rubber seal pads for leadwires = 5 hr/M		125.00/M
	Totals: costs	$ 55,800.00	$ 6,737.50/M

Concept B, Polypropylene, Glass Bead-Filled Molds:
(assumes 150 cycles per mold)

		Nonrecurring	Recurring
1.	Make mold with 7 pairs of cavities.	$ 45,000.00	
2.	Make rubber mold for leadwire sealoff.	2,800.00	
3.	Make rule die-cutter and air press for leadwire seals.	8,000.00	
4.	Make clamping fixtures to gang 7 mold sets together.		$ 6,500.00/M

		Nonrecurring	Recurring
5.	Mold plastic molds at 40-sec cycle for 7 sets of molds and setup = 2.4 hr/M molds.		60.00/M
6.	Mold and cut rubber seal pads for leadwires = 5 hr/M		125.00/M
	Totals: costs	$ 55,800.00	$ 6,685.00/M

Concept C, Premolded Integral Molds of Glass-Filled A.B.S., or Other Suitable Materials: (assumes one cycle per mold)

		Nonrecurring	Recurring
1.	Make injection mold with 7 pairs of cavities.	$ 45,000.00	
2.	Buy ultrasonic welder to assemble molds.	16,000.00	
3.	Make load/unload fixture for welder.	50,000.00	
4.	Mold integral molds at 2 cycles/min, 2.4 hr/M		60.00/M
	Totals: costs	$ 111,000.00	60.00/M

II. MOLD COST COMPARISONS

		Concept A Metal Molds	Concept B Plastic Molds	Concept C Integral Molds
1.	Longest cycling material will need 11,500 molds			
1.1	Contract cost	133,281	132,677	183,000
1.2	$ per 1,000 molds	111.07	110.56	152.50
2.	Shortest cycling material will need 4,000 metal molds or 8,000 plastic molds			
2.1	Contract cost	82,750	109,280	183,000

		Concept A Metal Molds	Concept B Plastic Molds	Concept C Integral Molds
2.2	$ per 1,000 molds	68.96	91.07	152.50
3.	Assembly cost factors which differ from one concept to another			
3.1	Load and close molds	4.2 hr/M	4.2 hr/M	1.6 hr/M
3.2	Clean and dry molds each cycle	7 hr/M	1.6 hr/M	0
3.3	Apply release agent and dry solvent	1.6 hr/M	0	0
3.4	Unload molds	2.8 hr	2.8 hr	0
3.5	Total hours per 1,000 units	15.6	8.6	1.6
3.6	Total $ per 1,000 units	390.00	215.00	40.0
3.7	Total contract costs.	$468,000	$258,000	$48,000
4.	Cost effectiveness			
4.1	Longest cycling material (needs most molds)			
4.1.1	Mold cost/contract	133,281	132,677	183,000
4.1.2	Assembly variable/ contract	468,000	258,000	48,000
4.1.3	Total contract cost	601,281	390,577	231,000
4.1.4	Cost in $ per 1,000 units	501.07	325.56	192.50
4.2	Shortest cycling material (needs least molds)			

APPENDIX A

		Concept A Metal Molds	Concept B Plastic Molds	Concept C Integral Molds
4.2.1	Mold cost/contract	82,750	109,280	183,000
4.2.2	Assembly variable/ contract	468,000	258,000	48,000
4.2.3	Total contract cost	550,750	367,280	231,000
4.2.4	Cost in $ per 1,000 units	458.95	306.07	192.50

APPENDIX B
STRESS RELIEF COATING: SUMMARY

		$ Per Year
MATERIAL:		
1.	Silicone rubber: 4,400 lb annually x $8.00/lb or 3.66 lb/M units = $29.33/M	35,200.00
2.	Solvent: 18,000 lb annually or 2,450 gal. annually, $1.25 gal. (2 gal/M = $2.55/M)	3,062.00
	Total Material:	$ 38,262.00
EQUIPMENT:		
1.	Blending tanks (2)	13,000.00
2.	Volumetric metering (1)	10,000.00
	Total mix equipment:	$ 23,000.00
MATERIAL PREPARATION LABOR:		
1.	Mixing and blending, 0.3 hr/M, or $7.50/M	9,000.00
2.	Receiving Inspection Quality Control, 26 batches at 4 hr at eng. rates = 0.09 hr/M or $3.03/M	3,640.00
3.	Line inspection for viscosity, 1 eng. hr/day = 0.2 hr/M or $7/M	8,400.00
4.	Production Engineer: 1 hr/day Support Specialist: 0.2 hr/day Q.C. Engineer: 1 hr/day	18,480.00
		$ 39,520.00
	Factory Labor $17.53/M	
	Eng. Support $15.40/M	
Material Total Cost:	$83.99/M parts, or:	$100,782.00

APPENDIX B

#1 Process: Coating approximately 3 selected sensitive components on a rotary application machine.

EQUIPMENT:		$ Per Year
1.	Rotary dial assembly machine with 7 work stations fed to metering at 3 stations by "material blending operation."	180,000.00
2.	Plastic handling trays (300 with capacity of 36 units each) ($2.50/tray).	750.00
3.	Steel carts with wheels, 6 shelves each and ventilated hold area, 24 carts at $500 each, $12,000 + vented area $6,000.00.	$ 18,000.00
		$198,750.00

APPLICATION LABOR:			
1.	Load and unload rotary machine from carts 3.2 hr/M or $80/M.		96,000.00
2.	Inspect coating 0.3 hr/M, $7.50/M		9,000.00
3.	Machine cleaning 0.2 hr/M, $5/M		6,000.00
4.	Production Engineer	1.0 hr/day	
5.	Support Specialist	0.2 hr/day	
6.	Q.C. Engineer	0.4 hr/day	13,440.00
			$124,440.00

Factory Labor	$92.50/M	
Eng. Support	$11.20/M	
Process 1 Total Cost:	$269.33/M or:	$323,190.00

#2 Process: Dip coat entire board assembly on a conveyorized, ventillated, dip and drying machine, including heat and humidity zone.

EQUIPMENT:		$ Per Year
1.	Conveyorized, vented, in-line tank assembly.	65,000.00
2.	Plastic handling trays, (150 with capacity of 36 units each) ($2.50 per tray).	375.00
3.	Steel carts with wheels, 6 shelves each and vented hold area, 12 carts at $500 each = $6,000.00, vented area $4,500.00.	10,500.00
		$ 75,875.00

APPLICATION LABOR:			
1.	Load and maintain tank, 0.32 hr/M, $8/M		9,600.00
2.	Load and unload machine to carts, 3.2 hr/M, $80/M		96,000.00
3.	Clean fixtures, 0.64 hr/M, $16/M		19,200.00
4.	Inspect coating 0.3 hr/M, $7.50/M		9,000.00
5.	Production Engineer	0.7 hr/day	
6.	Support Specialists	0.1 hr/day	
7.	Q.C. Engineer	0.3 hr/day	9,240.00
			$143,040.00

	Factory Labor	$111.50/M
	Eng. Support	$ 7.70/M

Process 2 Total Cost: $182.43/M or: $218,915.00

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APPENDIX C
MATERIAL TYPE COST COMPARISON

1.1 FILLED EPOXY, MH20245 (16 HOUR CURE AT 65°C)

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	88,860	
	1.2 Ovens for Preheating and Curing Coating	70,000	
	1.3 Dip Coater for Conformal Coating	75,875	
	1.4 Ventilation	10,000	
	1.5 Molds	0	
	SUBTOTAL	$ 244,735	$ 203.95
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	135,432	
	2.2 Conformal Coating	100,782	
	2.3 Purging Solvent	400	
	SUBTOTAL	$ 236,614	$ 197.18
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 10,713	$ 8.93
5.0	FLOOR SPACE (7,500 ft^2)	$ 90,000	$ 75.00
6.0	LABOR		
	6.1 Assembly	304,800	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	8,400	
	6.6 Receiving Inspection	14,700	
	SUBTOTAL	$ 399,900	$ 333.25
7.0	SCRAP AND SALVAGE RATE (0.5%)	$ 1,860	$ 1.55

APPENDIX C

		$ Per Year	$ Per 1000 Parts
8.0	SUMMARY		
	1.0	244,735	
	2.0	236,614	
	3.0	183,000	
	4.0	10,713	
	5.0	90,000	
	6.0	399,900	
	7.0	1,860	
9.0	TOTAL	$1,166,822	$ 972.35

1.2 FILLED EPOXY, EMERSON AND CUMING STYCAST 1495/CATALYST 9

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	88,860	
	1.2 Ovens for Preheating and Curing	35,000	
	1.3 Dip Coater for Conformal Coating	75,875	
	1.4 Ventilation	6,500	
	1.5 Molds	0	
	SUBTOTAL	$ 206,235	$ 171.86
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	119,028	
	2.2 Conformal Coating	100,782	
	2.3 Purging Solvent	400	
	SUBTOTAL	$ 220,210	$ 183.51
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 4,600	$ 3.83
5.0	FLOOR SPACE (4,800 ft^2)	$ 57,600	$ 48.00
6.0	LABOR		
	6.1 Assembly	304,800	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	8,400	
	6.6 Receiving Inspection	14,700	
	SUBTOTAL	$ 399,900	$ 333.25
7.0	SCRAP AND SALVAGE RATE (0.5%)	$ 1,860	$ 1.55
8.0	SUMMARY		
	1.0	206,235	
	2.0	220,210	
	3.0	183,000	
	4.0	4,600	
	5.0	57,600	
	6.0	399,900	
	7.0	1,860	
9.0	TOTAL	$1,073,405	$ 894.50

APPENDIX C

2.1 FILLED EPOXY, SINGLE COMPONENT, HYSOL E0-0029

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	32,000	
	1.2 Ovens for Preheating and Curing	70,000	
	1.3 Dip Coater for Conformal Coating	75,875	
	1.4 Ventilation	10,000	
	1.5 Molds	0	
	SUBTOTAL	$ 187,875	$ 156.56
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	156,408	
	2.2 Conformal Coating	100,782	
	2.3 Purging Solvent	0	
	SUBTOTAL	$ 257,190	$ 214,32
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 9,850	$ 8.21
5.0	FLOOR SPACE (6,300 ft^2)	$ 75,600	$ 63.00
6.0	LABOR		
	6.1 Assembly	268,800	
	6.2 Inspection	25,000	
	6.3 Production Engineer	25,000	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	5,000	
	6.6 Receiving Inspection	1,860	
	SUBTOTAL	$ 342,460	$ 285.38
7.0	SCRAP AND SALVAGE RATE (0.3%)	$ 1,344	$ 1.12
8.0	SUMMARY		
	1.0	187,875	
	2.0	257,190	
	3.0	183,000	
	4.0	9,850	
	5.0	75,600	
	6.0	342,460	
	7.0	1,344	
9.0	TOTAL	$1,057,319	$ 881.10

3.1 RIGID SYNTACTIC FOAM, FORMULATED RESINS PR 2036

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	88,860	
	1.2 Ovens for Preheating and Curing	40,000	
	1.3 Dip Coater for Conformal Coating	0	
	1.4 Ventilation	7,000	
	1.5 Molds	0	
	SUBTOTAL	$ 135,860	$ 113.22
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	104,100	
	2.2 Conformal Coating	0	
	2.3 Purging Solvent	400	
	SUBTOTAL	$ 104,500	$ 87.08
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 5,000	$ 4.16
5.0	FLOOR SPACE (5,000 ft^2)	$ 60,000	$ 50.00
6.0	LABOR		
	6.1 Assembly	216,000	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	16,800	
	6.6 Receiving Inspection	14,700	
	SUBTOTAL	$ 319,500	$ 266.25
7.0	SCRAP AND SALVAGE RATE (2.5%)	$ 5,400	$ 4.50
8.0	SUMMARY		
	1.0	135,860	
	2.0	104,500	
	3.0	183,000	
	4.0	5,000	
	5.0	60,000	
	6.0	319,500	
	7.0	5,400	
9.0	TOTAL	$ 813,260	$ 677.72

APPENDIX C

3.2 RIGID SYNTACTIC FOAM, 3M XR5090

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	88,860	
	1.2 Ovens for Preheating and Curing	45,000	
	1.3 Dip Coater for Conformal Coating	0	
	1.4 Ventilation	7,000	
	1.5 Molds	0	
	SUBTOTAL	$ 140,860	$ 117.38
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	493,308	
	2.2 Conformal Coating	0	
	2.3 Purging Solvent	400	
	SUBTOTAL	$ 493,708	$ 411.42
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 5,300	$ 4.42
5.0	FLOOR SPACE (5,600 ft^2)	$ 67,200	$ 56.00
6.0	LABOR		
	6.1 Assembly	216,000	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	16,800	
	6.6 Receiving Inspection	14,700	
	SUBTOTAL	$ 319,500	$ 266.25
7.0	SCRAP AND SALVAGE RATE (2.5%)	$ 5,400	$ 4.50
8.0	SUMMARY		
	1.0	140,860	
	2.0	493,708	
	3.0	183,000	
	4.0	5,300	
	5.0	67,200	
	6.0	319,500	
	7.0	5,400	
9.0	TOTAL	$1,214,968	$1,012.47

4.1 RIGID SYNTACTIC FOAM, SINGLE-COMPONENT, HYSOL NB 509-70-2

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	32,000	
	1.2 Ovens for Preheating and Curing	70,000	
	1.3 Dip Coater for Conformal Coating	0	
	1.4 Ventilation	10,000	
	1.5 Molds	0	
	SUBTOTAL	$ 112,000	$ 99.33
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	255,528	
	2.2 Conformal Coating	0	
	2.3 Purging Solvent	0	
	SUBTOTAL	$ 255,528	$ 212.94
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 9,850	$ 8.21
5.0	FLOOR SPACE (4,500 ft^2)	$ 54,000	$ 45.00
6.0	LABOR		
	6.1 Assembly	180,000	
	6.2 Inspection	25,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	5,000	
	6.6 Receiving Inspection	1,860	
	SUBTOTAL	$ 253,860	$ 211.55
7.0	SCRAP AND SALVAGE RATE (1.5%)	$ 2,700	$ 2.25
8.0	SUMMARY		
	1.0	112,000	
	2.0	255,528	
	3.0	183,000	
	4.0	9,850	
	5.0	54,000	
	6.0	253,860	
	7.0	2,700	
9.0	TOTAL	$ 870,938	$ 725.78

APPENDIX C

5.1 CHEMICALLY BLOWN FOAM, COOK CORO-FOAM 589

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	30,000	
	1.2 Ovens for Preheating and Curing	0	
	1.3 Dip Coater for Conformal Coating	0	
	1.4 Ventilation	15,000	
	1.5 Molds	0	
	SUBTOTAL	$ 45,000	$ 37.20
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	14,461	
	2.2 Conformal Coating	0	
	2.3 Purging Solvent	1,000	
	SUBTOTAL	$ 15,461	$ 12.88
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 691	$ 0.58
5.0	FLOOR SPACE (3,500 ft^2)	$ 42,000	$ 35.00
6.0	LABOR		
	6.1 Assembly	192,000	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	12,000	
	6.6 Receiving Inspection	2,625	
	SUBTOTAL	$ 278,625	$ 232.18
7.0	SCRAP AND SALVAGE RATE (15%)	$ 28,800	$ 24.00
8.0	SUMMARY		
	1.0	45,000	
	2.0	15,461	
	3.0	183,000	
	4.0	691	
	5.0	42,000	
	6.0	278,625	
	7.0	28,800	
9.0	TOTAL	$ 593,577	$ 494.64

5.2 CHEMICALLY BLOWN FOAM, WITCO ISOFOAM PE-18

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	30,000	
	1.2 Ovens for Preheating and Curing	35,000	
	1.3 Dip Coater for Conformal Coating	0	
	1.4 Ventilation	18,000	
	1.5 Molds	0	
	SUBTOTAL	$ 83,000	$ 69.16
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	19,622	
	2.2 Conformal Coating	0	
	2.3 Purging Solvent	1,000	
	SUBTOTAL	$ 20,622	$ 17.18
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 4,600	$ 3.83
5.0	FLOOR SPACE (4,800 ft^2)	$ 57,600	$ 48.00
6.0	LABOR		
	6.1 Assembly	252,000	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	12,000	
	6.6 Receiving Inspection	2,625	
	SUBTOTAL	$ 338,625	$ 282.18
7.0	SCRAP AND SALVAGE RATE (15%)	$ 37,800	$ 31.50
8.0	SUMMARY		
	1.0	83,000	
	2.0	20,622	
	3.0	183,000	
	4.0	4,600	
	5.0	57,600	
	6.0	338,625	
	7.0	37,800	
9.0	TOTAL	$ 725,247	$ 604.37

APPENDIX C

6.1 SEMIRIGID URETHANE, DOW ISP-100

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	88,860	
	1.2 Ovens for Preheating and Curing	20,000	
	1.3 Dip Coater for Conformal Coating	75,875	
	1.4 Ventilation	10,000	
	1.5 Molds	0	
	SUBTOTAL	$ 194,735	$ 162.28
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	52,219	
	2.2 Conformal Coating	100,782	
	2.3 Purging Solvent	700	
	SUBTOTAL	$ 153,701	$ 128.08
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 4,032	$ 3.36
5.0	FLOOR SPACE (6,000 ft^2)	$ 72,000	$ 60.00
6.0	LABOR		
	6.1 Assembly	268,800	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	12,000	
	6.6 Receiving Inspection	4,375	
	SUBTOTAL	$ 357,175	$ 297.65
7.0	SCRAP AND SALVAGE RATE (0.5%)	$ 1,344	$ 1.12
8.0	SUMMARY		
	1.0	194,735	
	2.0	153,701	
	3.0	183,000	
	4.0	4,032	
	5.0	72,000	
	6.0	357,175	
	7.0	1,344	
9.0	TOTAL	$ 965,987	$ 804.98

7.1 FLEXIBLE ELASTOMER, UNIROYAL B635

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Meter/Mix Machine	88,860	
	1.2 Ovens for Preheating and Curing	30,000	
	1.3 Dip Coater for Conformal Coating	0	
	1.4 Ventilation	10,000	
	1.5 Molds	0	
	SUBTOTAL	$ 128,860	$ 107.38
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	110,474	
	2.2 Conformal Coating	0	
	2.3 Purging Solvent	700	
	SUBTOTAL	$ 111,174	$ 92.65
3.0	INTEGRAL MOLDS	$ 183,000	$ 152.50
4.0	ENERGY	$ 5,000	$ 4.16
5.0	FLOOR SPACE (6,000 ft^2)	$ 72,000	$ 60.00
6.0	LABOR		
	6.1 Assembly	180,000	
	6.2 Inspection	30,000	
	6.3 Production Engineer	25,200	
	6.4 Quality Engineer	16,800	
	6.5 Support Specialist	12,000	
	6.6 Receiving Inspection	4,375	
	SUBTOTAL	$ 268,375	$ 223.65
7.0	SCRAP AND SALVAGE RATE (0.5%)	$ 900	$ 0.75
8.0	SUMMARY		
	1.0	128,860	
	2.0	111,174	
	3.0	183,000	
	4.0	5,000	
	5.0	72,000	
	6.0	268,375	
	7.0	900	
9.0	TOTAL	$ 769,309	$ 641.09

APPENDIX C

8.1 TRANSFER MOLDED EPOXY, HYSOL MG5F (15 MINUTE CYCLE)

	NONRECURRING COST	$ Per Ye -	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Carrousel Transfer Molding Machine	460,000	
	1.2 Ovens for Preheating and Curing	0	
	1.3 Dip Coater for Conformal Coating	75,875	
	1.4 Ventilation	8,500	
	1.5 Molds	180,000	
	SUBTOTAL	$ 724,375	$ 603.65
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	260,503	
	2.2 Conformal Coating	100,782	
	2.3 Purging Solvent	0	
	SUBTOTAL	$ 361,285	$ 301.07
3.0	INTEGRAL MOLDS	$ 0	
4.0	ENERGY	$ 11,923	$ 9.94
5.0	FLOOR SPACE (3,000 ft^2)	$ 36,000	$ 30.00
6.0	LABOR		
	6.1 Assembly	48,000	
	6.2 Inspection	9,000	
	6.3 Production Engineer	16,800	
	6.4 Quality Engineer	5,040	
	6.5 Support Specialist	2,520	
	6.6 Receiving Inspection	5,040	
	SUBTOTAL	$ 86,400	$ 72.00
7.0	SCRAP AND SALVAGE RATE (0.5%)	$ 1,224	$ 1.02
8.0	SUMMARY		
	1.0	724,375	
	2.0	361,285	
	3.0	0	
	4.0	11,923	
	5.0	36,000	
	6.0	86,400	
	7.0	1,224	
9.0	TOTAL	$1,221,207	$1,017.67

8.2 TRANSFER MOLDED EPOXY, HYSOL MG5F (1 MINUTE CYCLE)

	NONRECURRING COST	$ Per Year	$ Per 1000 Parts
1.0	FACILITY		
	1.1 Transfer Molding Press	70,000	
	1.2 Ovens for Preheating and Curing	0	
	1.3 Dip Coater for Conformal Coating	75,875	
	1.4 Ventilation	2,500	
	1.5 Molds	22,500	
	SUBTOTAL	$ 170,875	$ 142.39
	RECURRING COST		
2.0	MATERIAL		
	2.1 Encapsulant	260,503	
	2.2 Conformal Coating	100,782	
	2.3 Purging Solvent	0	
	SUBTOTAL	$ 361,285	$ 301.07
3.0	INTEGRAL MOLDS	$ 0	
4.0	ENERGY	$ 1,958	$ 1.63
5.0	FLOOR SPACE (500 ft^2)	$ 6,000	$ 5.00
6.0	LABOR		
	6.1 Assembly	36,000	
	6.2 Inspection	9,000	
	6.3 Production Engineer	8,400	
	6.4 Quality Engineer	5,040	
	6.5 Support Specialist	2,520	
	6.6 Receiving Inspection	5,040	
	SUBTOTAL	$ 66,000	$ 55.00
7.0	SCRAP AND SALVAGE RATE (0.5%)	$ 1,224	$ 1.02
8.0	SUMMARY		
	1.0	170,875	
	2.0	361,285	
	3.0	0	
	4.0	1,958	
	5.0	6,000	
	6.0	66,000	
	7.0	1,224	
9.0	TOTAL	$ 607,342	$ 506.11

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APPENDIX D
INFRARED SPECTRA FOR 10 CANDIDATE MATERIALS

The infrared spectra for the 10 candidate materials are shown in Figures D-1 through D-18.

APPENDIX D

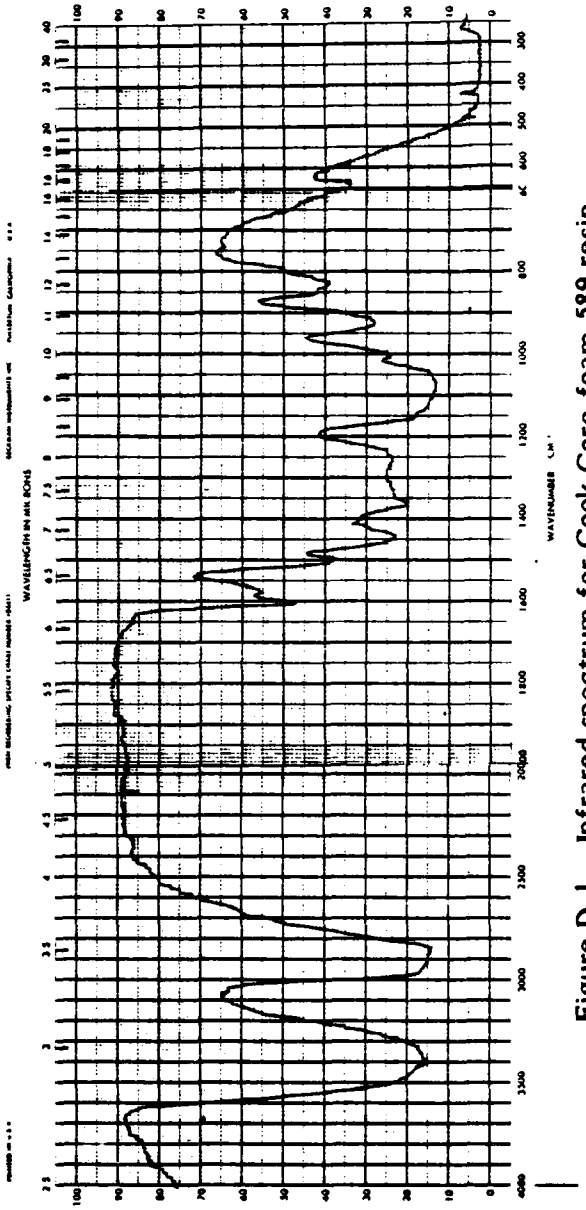

Figure D-1. Infrared spectrum for Cook Coro-foam 589 resin.

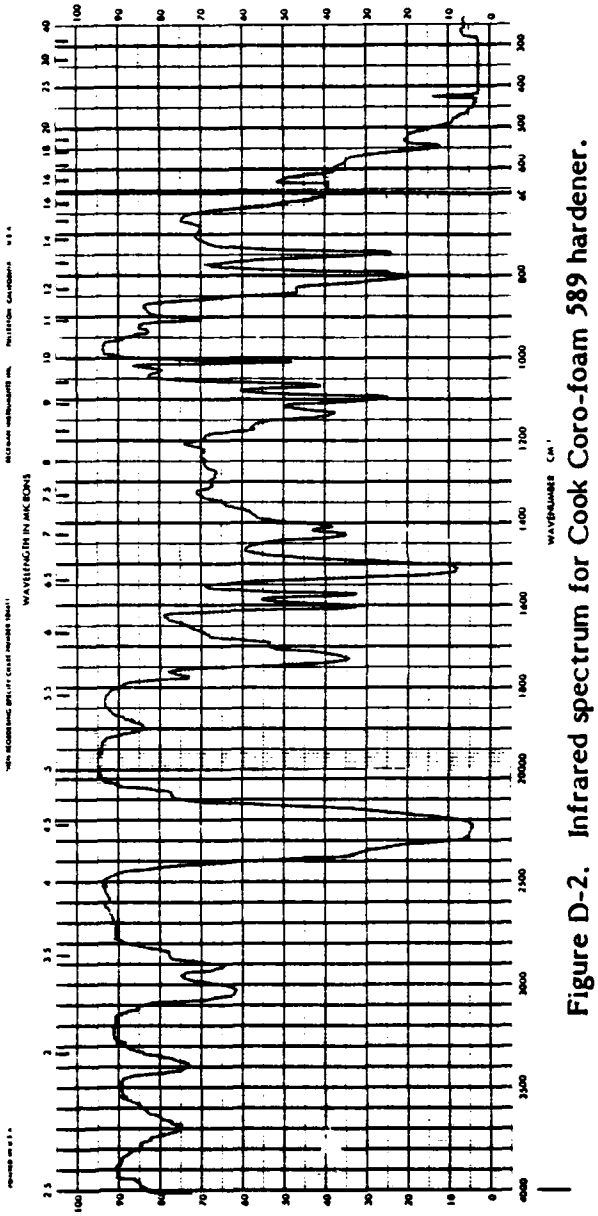

Figure D-2. Infrared spectrum for Cook Coro-foam 589 hardener.

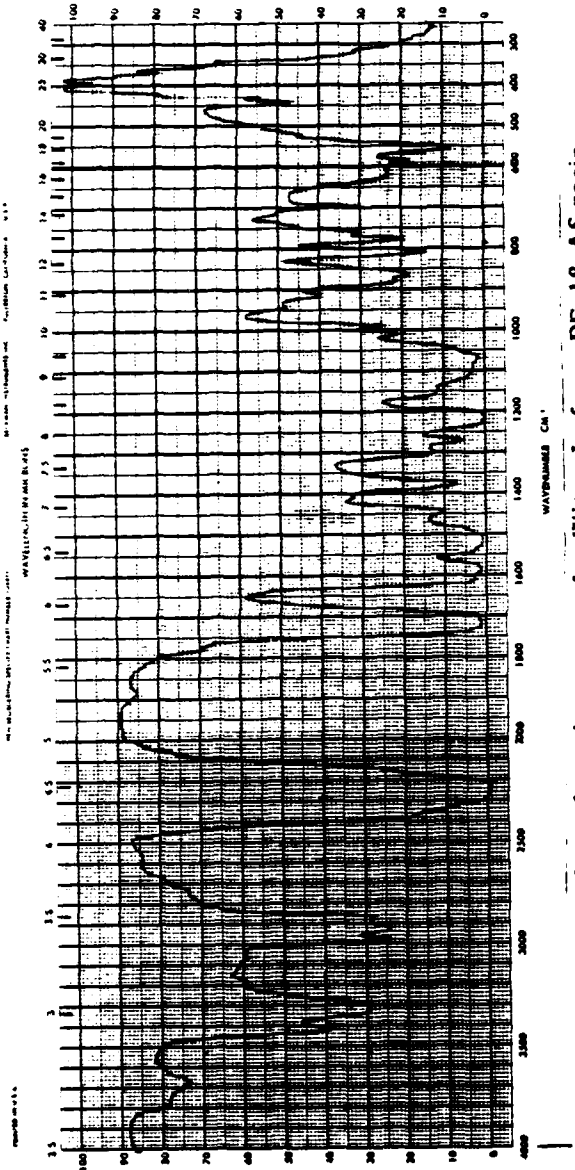

Figure D-3. Infrared spectrum for Witco Isofoam PE-18-AS resin.

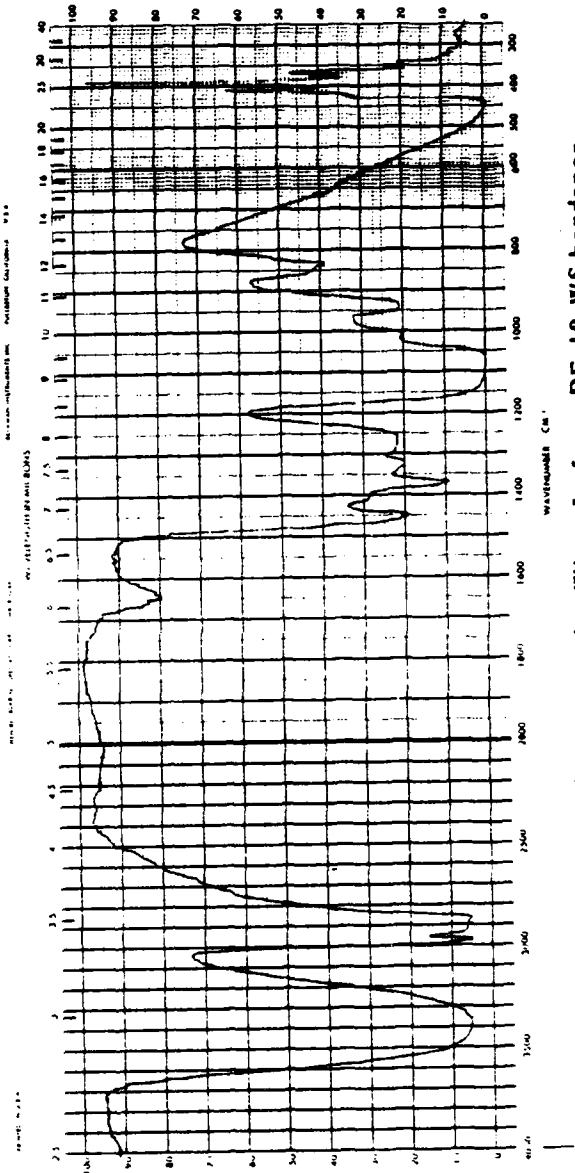

Figure D-4. Infrared spectrum for Witco Isofoam PE-18-WS hardener.

APPENDIX D

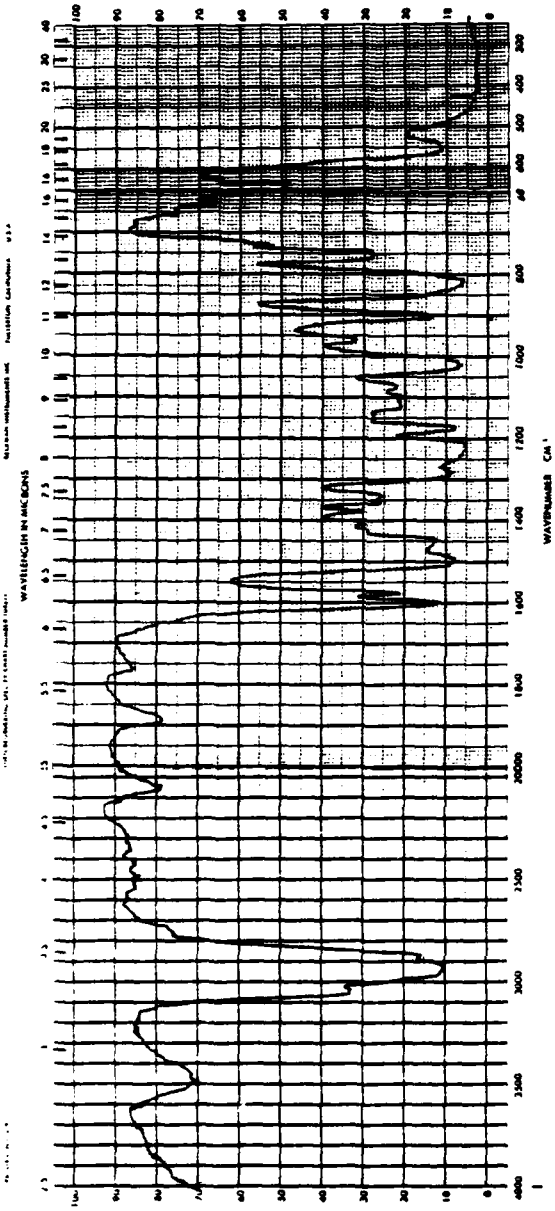

Figure D-5. Infrared spectrum for Formulated Resin PR2036 resin.

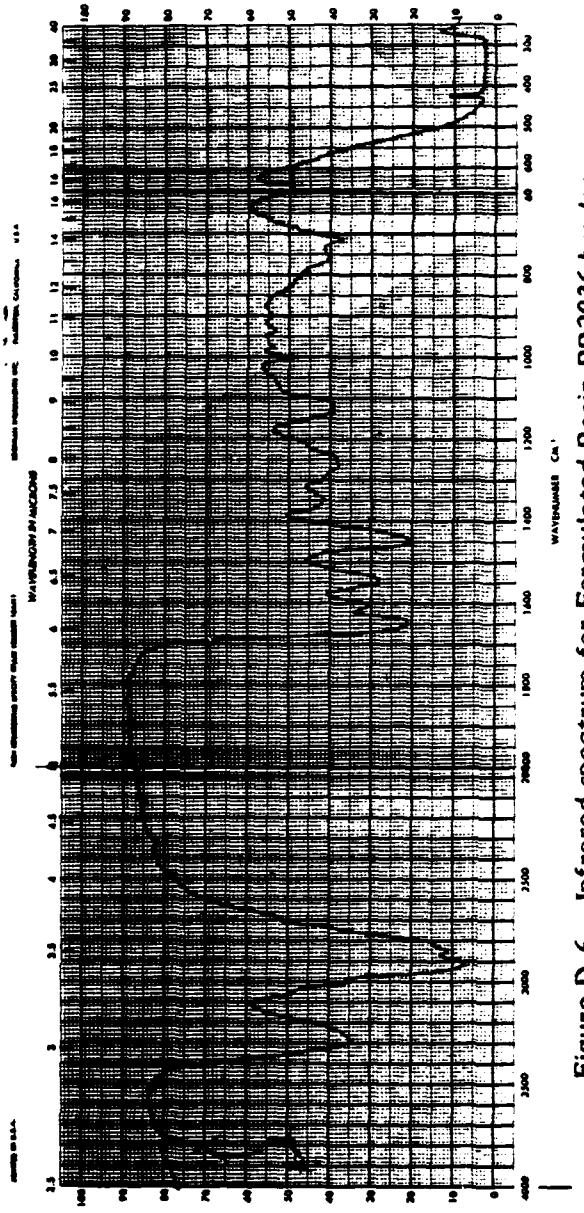

Figure D-6. Infrared spectrum for Formulated Resin PR2036 hardener.

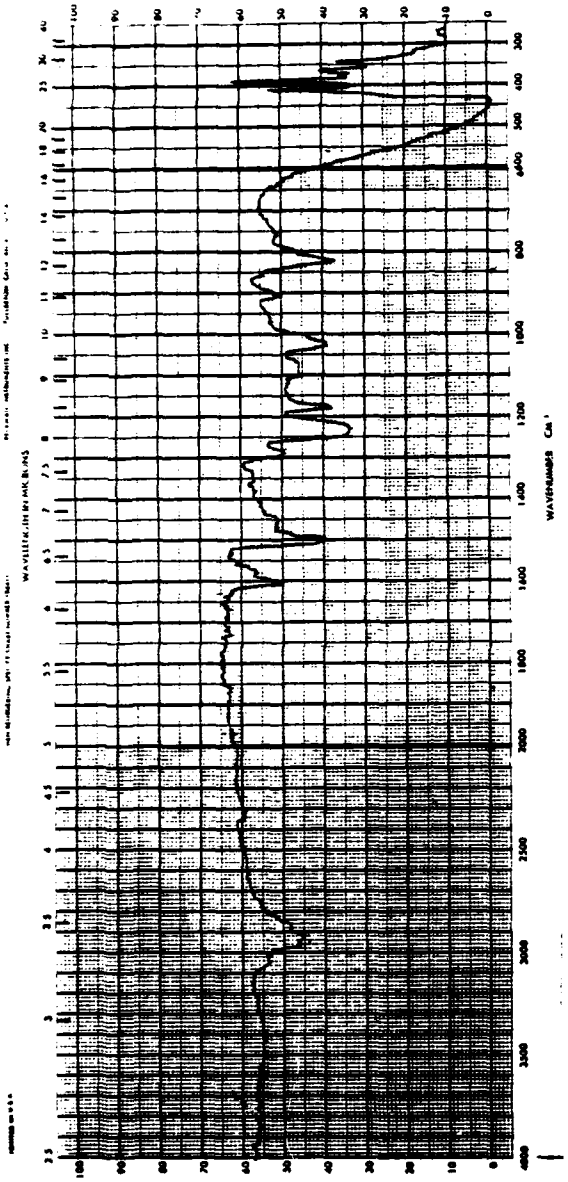

Figure D-7. Infrared spectrum for 3M Scotchcast XR5090 resin.

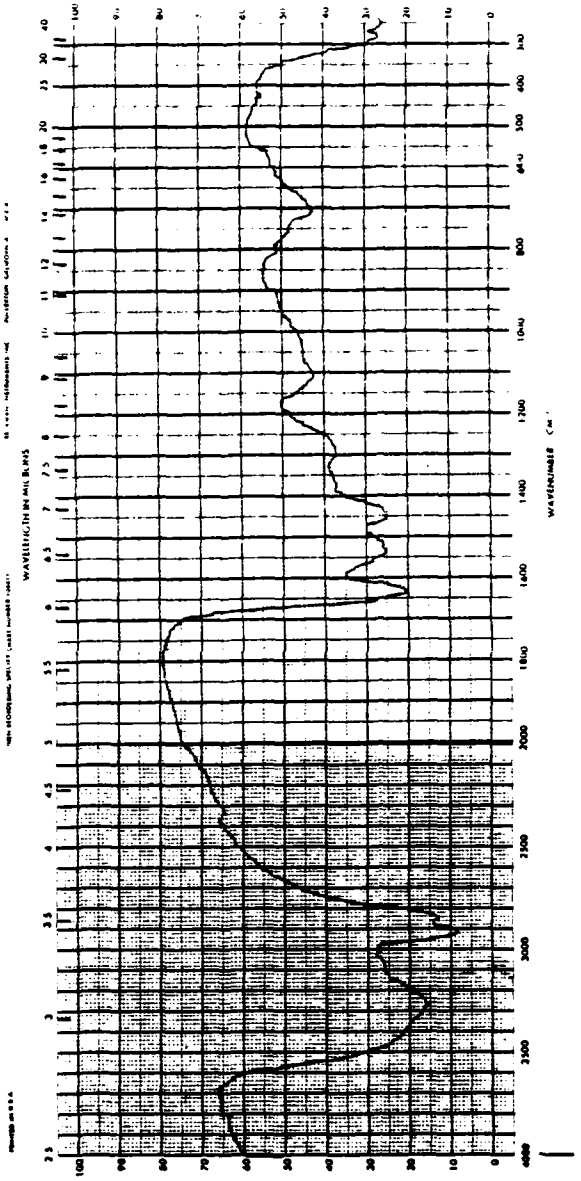

Figure D-8. Infrared spectrum for 3M Scotchcast XR5090 hardener.

APPENDIX D

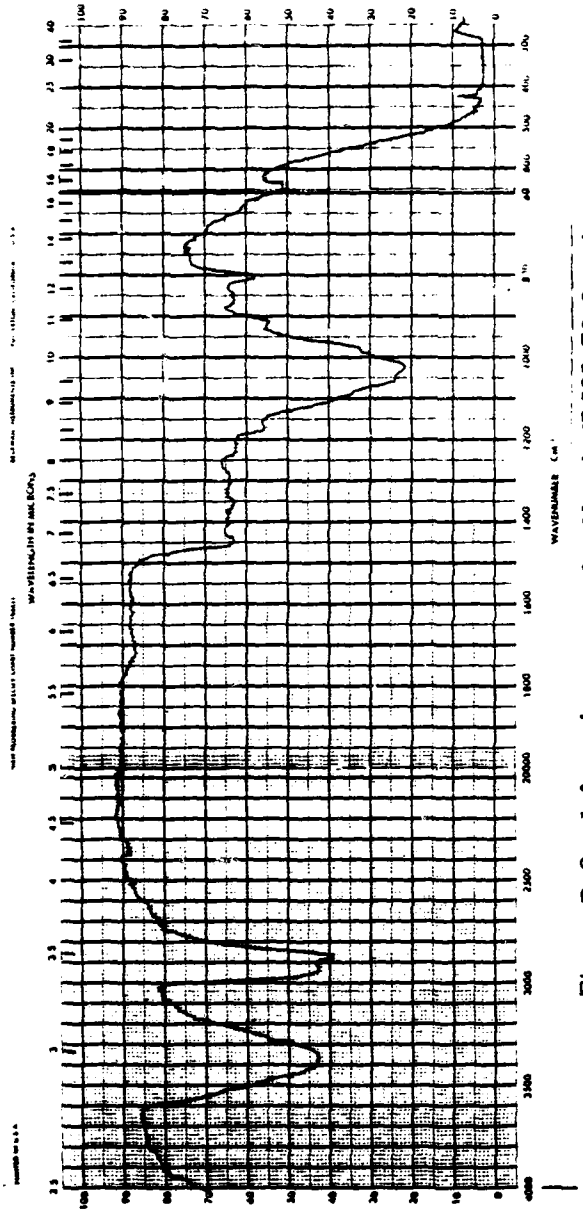

Figure D-9. Infrared spectrum for Hysol NB509-70-2 resin.

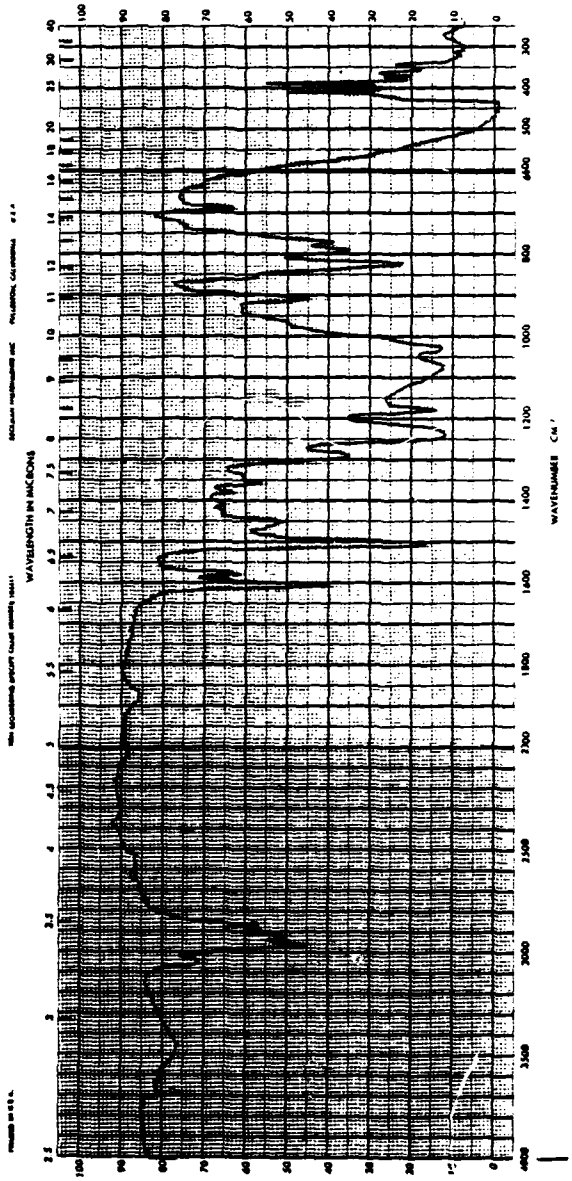

Figure D-10. Infrared spectrum for Emerson and Cuming Stycast 1495 resin.

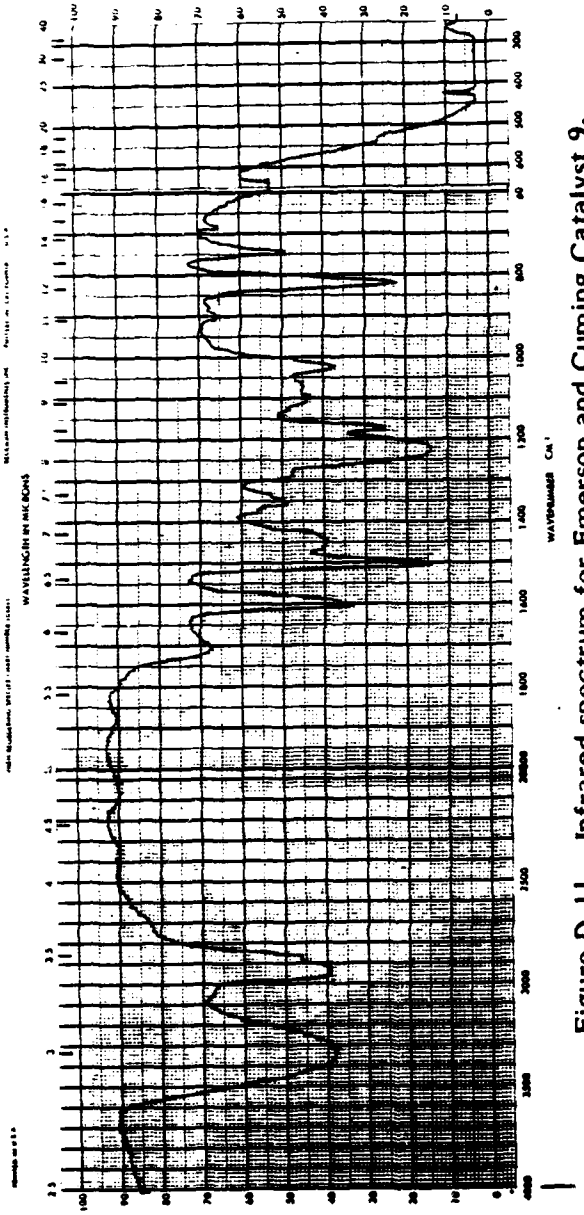

Figure D-11. Infrared spectrum for Emerson and Cuming Catalyst 9.

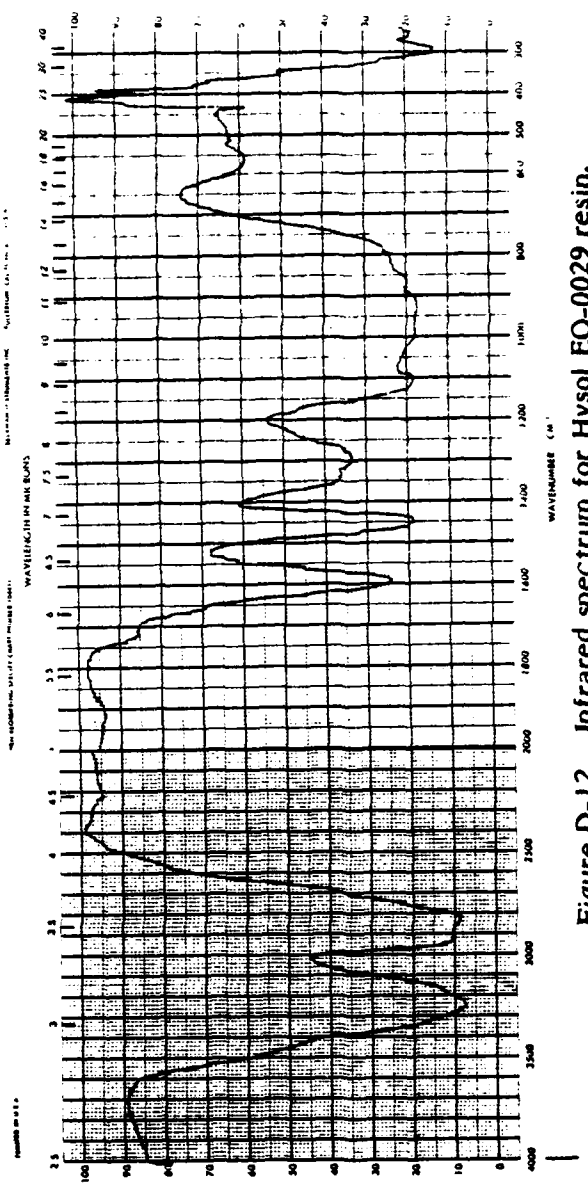

Figure D-12. Infrared spectrum for Hysol EO-0029 resin.

APPENDIX D

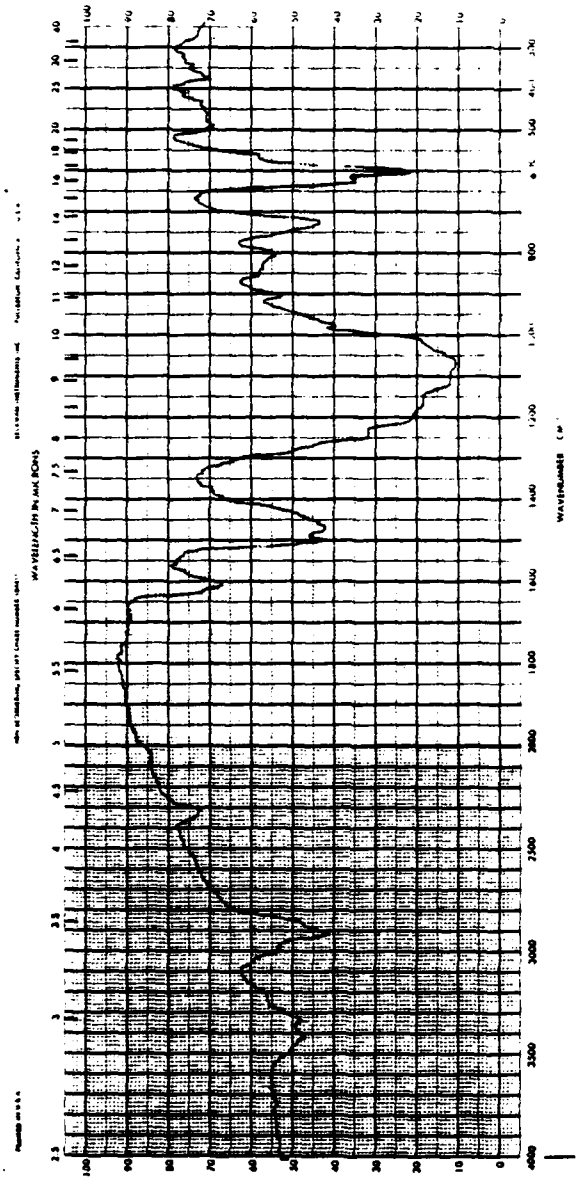

Figure D-13. Infrared spectrum for Hysol Hiflow MG5F molding compound.

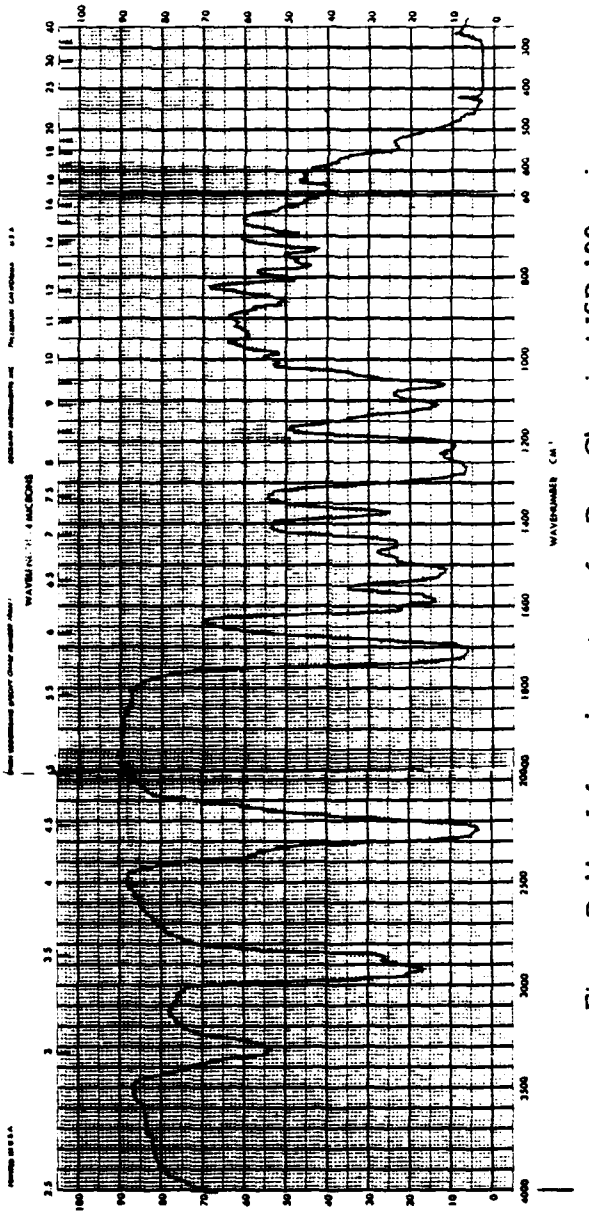

Figure D-14. Infrared spectrum for Dow Chemical ISP-100 resin.

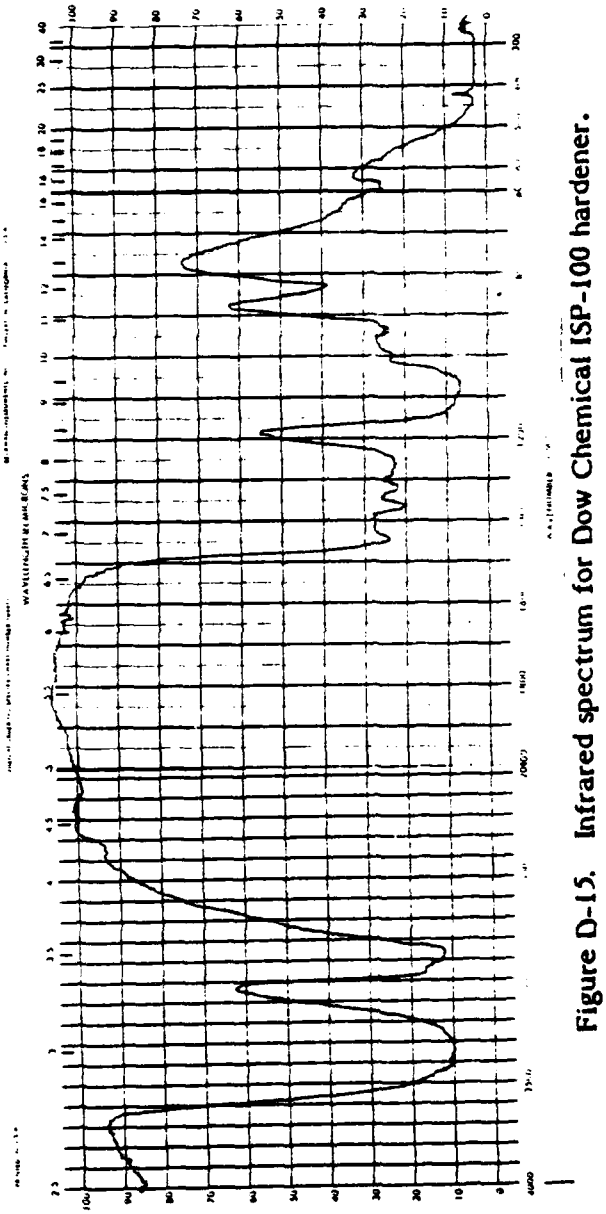

Figure D-15. Infrared spectrum for Dow Chemical ISP-100 hardener.

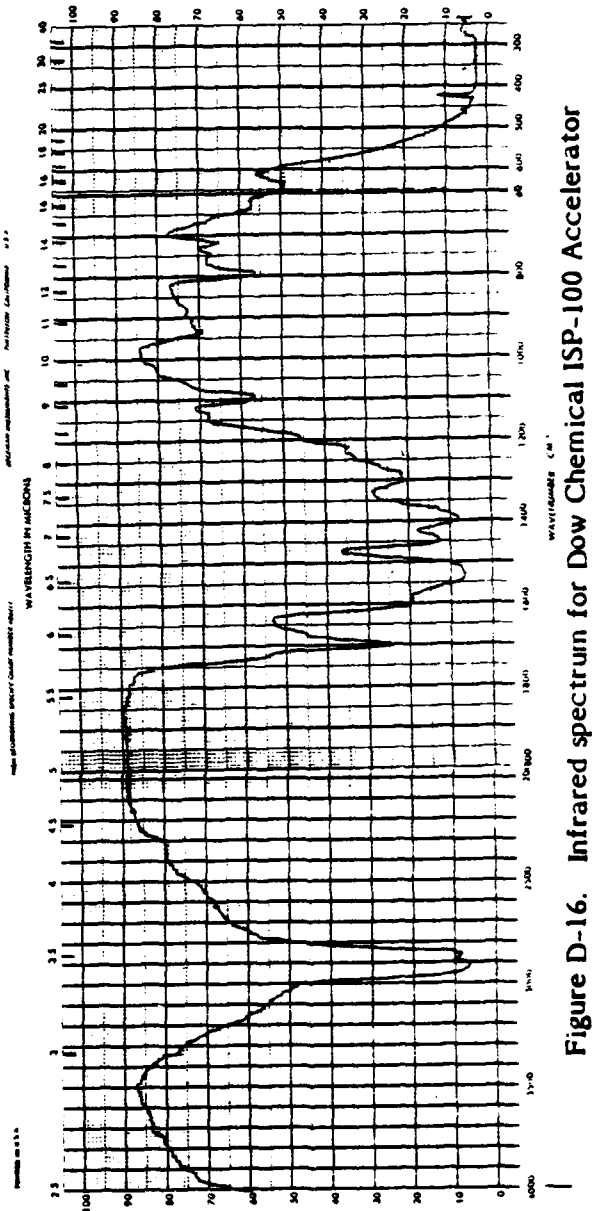

Figure D-16. Infrared spectrum for Dow Chemical ISP-100 Accelerator (Witco Fomrez C-2).

APPENDIX D

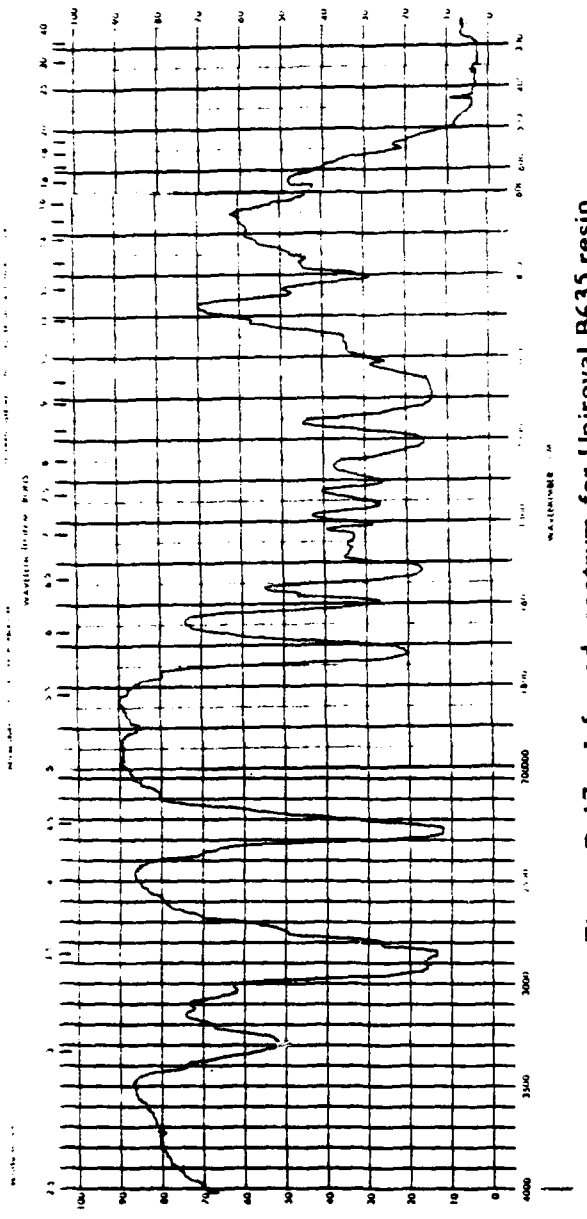

Figure D-17. Infrared spectrum for Uniroyal B635 resin.

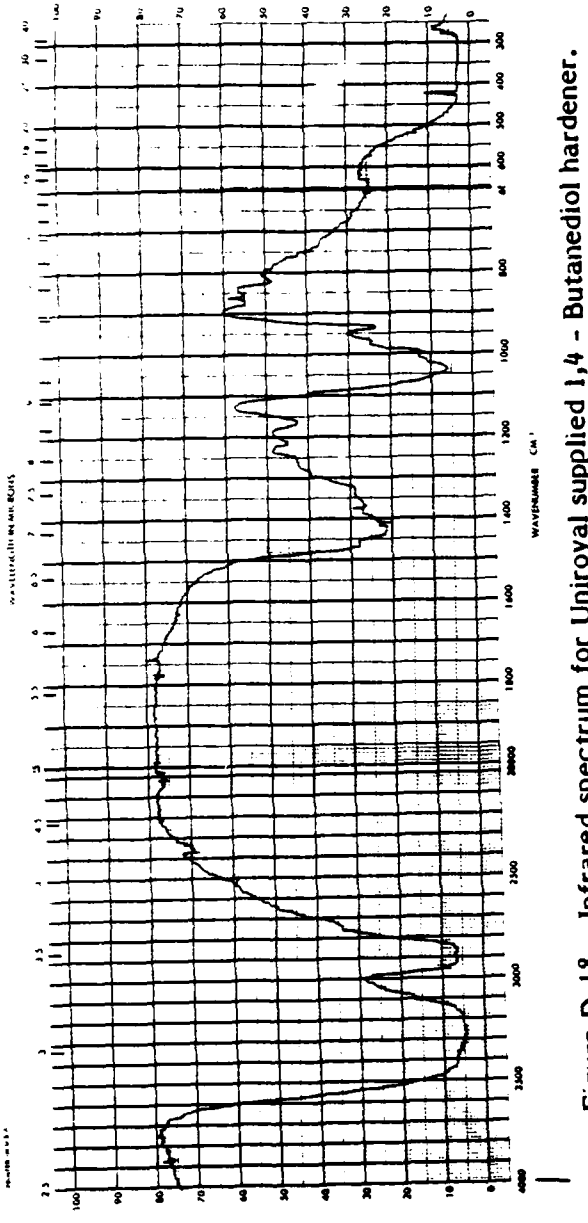

Figure D-18. Infrared spectrum for Uniroyal supplied 1,4 - Butanediol hardener.

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